APPENDIX 2

SAFETY ANALYSIS REPORT FOR 24.8 kW HELIUM REFRIGERATOR

D. P. Brown
12/20/83
Rev. B, 12/6/84

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

1.0 INTRODUCTION

This report addresses the safety items which have been considered with respect to the design, fabrication and operation of the BNL 24.8 kW Helium Refrigerator. This refrigerator was intended to serve the magnets for the ISABELLE/CBA project. With the present uncertainty as to its final use, no attempt has been made in this report to describe any parts of the cryogenic system (i.e., the helium distribution system and the magnet/cryogenic interface) beyond those required for the refrigerator acceptance test. The acceptance test is to verify that the equipment supplied by the vendor meets the BNL specification. This report will describe the architectural features of buildings which enclose this equipment, the refrigerator itself and the principal hazards associated with the operation of this equipment.

This refrigerator is the latest and largest of a series of 4.5°K helium refrigerators owned and operated by BNL. Some very small liquefiers were used in the Chemistry Department for a number of years prior to 1966 when the first closed-cycle helium refrigerator (175 W) began operation at BNL. This refrigerator is still in use today (Bldg. 902). Since then several refrigerators with 100 W capacity have been installed at BNL and also refrigerators with capacities of 700 W, 1580 W, 600 W and 1100 W. All of the larger refrigerators were intended to provide the necessary cooling for a magnet or a system of magnets for the Accelerator Department.

There have never been any accidents associated with the operation of any of these refrigerators. Cumulatively they have been operative for about 65 years. While the new refrigerator dwarfs the old ones in size, it shares with them the feature that it does not represent a significant hazard beyond that found in many other industrial-type environments of equivalent size.

The refrigeration equipment is installed in two buildings and the out-of-doors areas adjacent to those buildings. The Cryogenic Building is wall-to-wall with the Collider Center and contains the cold boxes (vacuum-jacketed enclosures for the heat exchangers, valves, etc.) and their ancillary equipment (turboexpanders, adsorbers, etc.). Nearby is the Compressor Building which contains the helium compression and gas handling equipment. A large cooling tower is provided to reject the heat of compression which is transferred to the cooling water. Two pipes connect this equipment with an existing gas storage area formerly used to store gas for the 80-inch and 7-foot Bubble Chambers.

2.0 FACILITY DESCRIPTION

2.1 Architectural

The Helium Refrigerator System is housed in two structures which are part of the Collider Center Complex. See Figure 2-1.

A. The Cryogenic Building (see Figure 2-2 and 2-3) is a high bay, concrete block building of approximately 7,000 square feet and is located immediately west of and contiguous to the Collider Center. Though contiguous, the two buildings are structurally separate to insure acceptable acoustic levels in the Collider Center. The Cryogenic Building includes an 18-foot by 50-foot truck service platform. Access is through a 12-foot by 12-foot roll-up door.

The entire area of the Cryogenic Building is serviced by a 10-ton overhead bridge crane. The truck service platform and adjacent cryogenic equipment mezzanine is at the same floor elevation as the ground floor elevation of the Collider Center. The mezzanine floor has an area of approximately 3,000 square feet and is comprised entirely of removable steel grating sections.

The 6000 square foot cryogenic equipment floor is located 10 feet below ground floor level and is also serviced by an overhead 10-ton crane.

The exterior of the building is comprised of concrete block with five approximately 16 foot square openings on the north side through which the Cold Boxes were installed. These openings were then sealed to the vacuum tanks of the Cold Boxes.

The roof system is comprised of a 3-ply built-up asphalt and felt membrane over insulation and metal deck and topped with aggregate surfacing. Drainage is accomplished by a system of roof drains carrying water below grade to a pumped ejector thence to a manhole located outside the north side of the building.

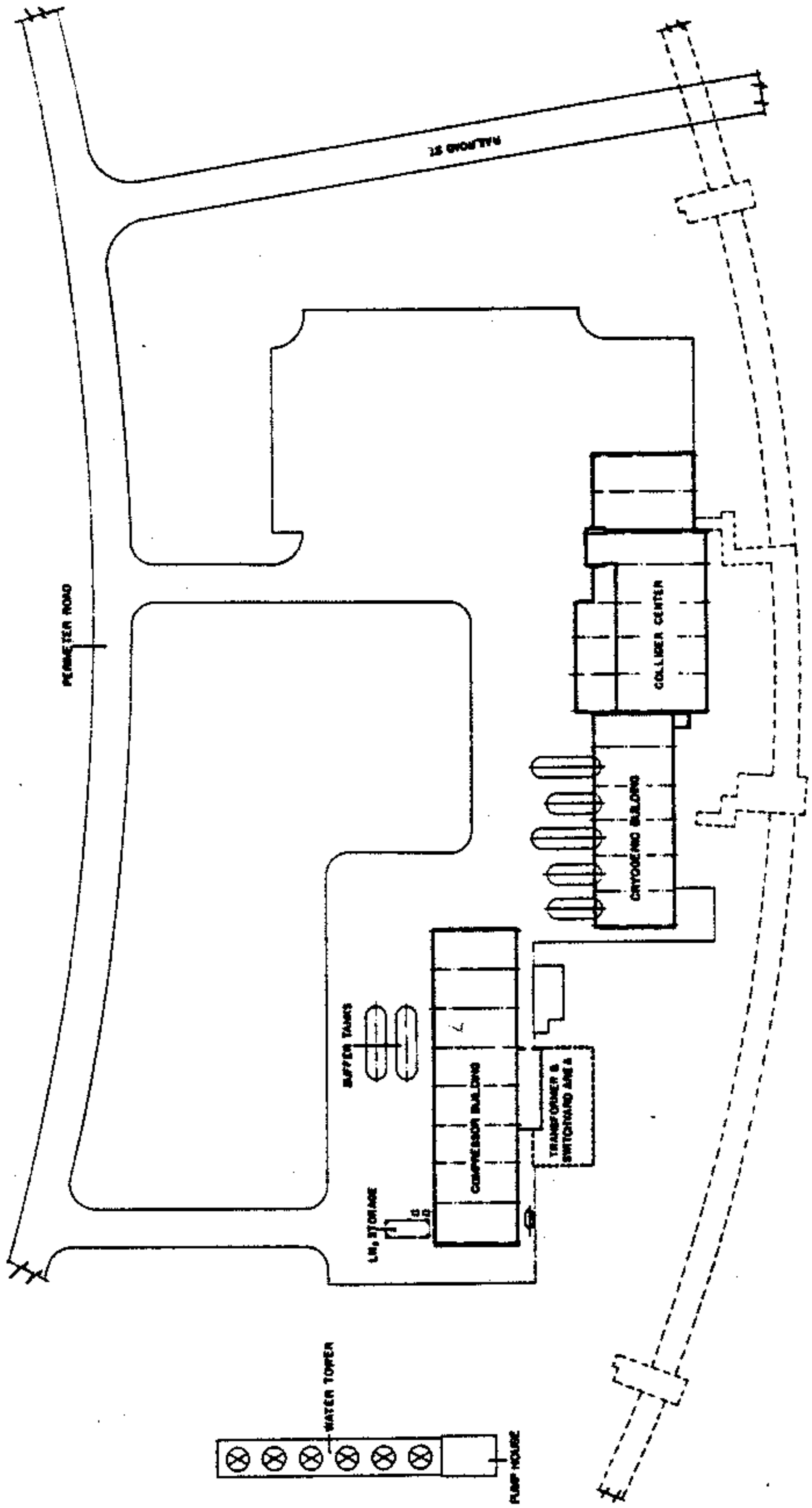


Figure 2-1
Site Plan

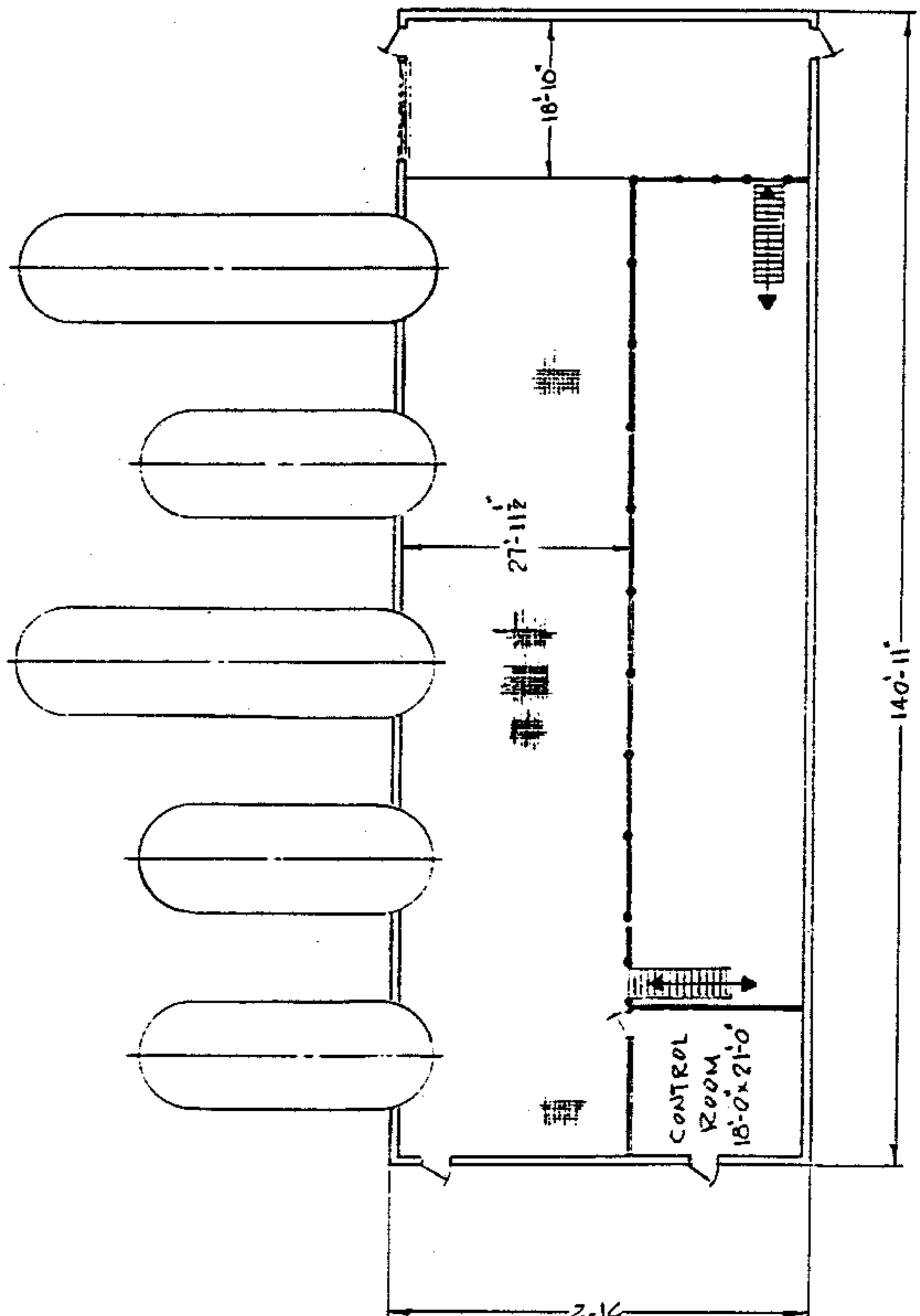


Figure 2-2
Cryogenic Building Plan

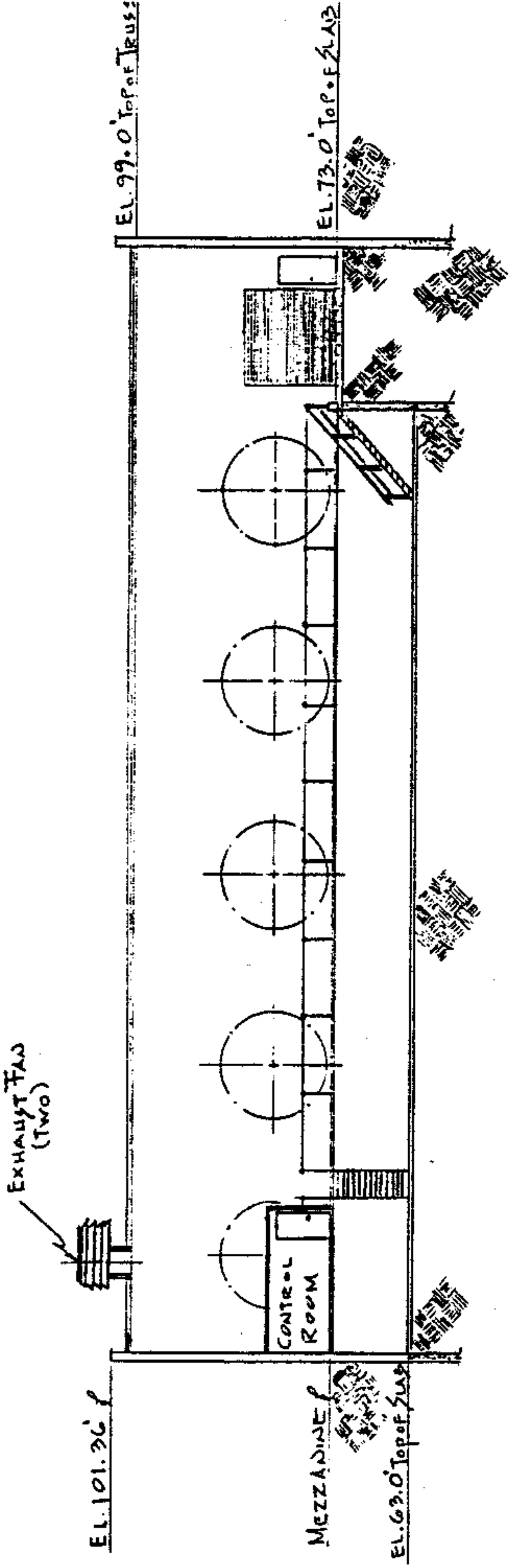


Figure 2-3
Cryogenic Building Elevation

B. The Helium Compressor Building (see Figure 2-4) is a one story, high bay, concrete block structure of approximately 10,000 square feet floor area. It houses the helium compressors and their associated equipment. It is located northwest of the Cryogenic Building.

The entire floor area is serviced by a 10-ton overhead bridge crane. The building exterior, roofing and drainage systems are the same as described for the Cryogenic Building. A motor control center appendage is located on the south side of the facility and is of similar concrete block construction.

2.1.1 Site

The Cryogenic and Compressor Buildings are located north of and parallel to Sextant 5 of the Accelerator Magnet Enclosure. The complex is accessed from the main laboratory site through Railroad Street and the Perimeter Road (see Figure 2-1).

2.1.~~3~~2 Structural

The structural systems of the Cryogenic and Compressor Buildings consist of 50-foot trusses with long span steel joist purlins supporting an insulated metal deck roof. Both systems support a 10-ton bridge crane servicing the entire floor area.

In addition the Cryogenic Building has a removable structural grating floor at grade elevation to support cold box turbine pods and piping.

2.1.3 Exits

A. Cryogenic Building exits are as follows:

1. 3'-4" x 7'-2" hollow metal door and adjacent 12' x 12' roll-up door on the north side at northeast corner.

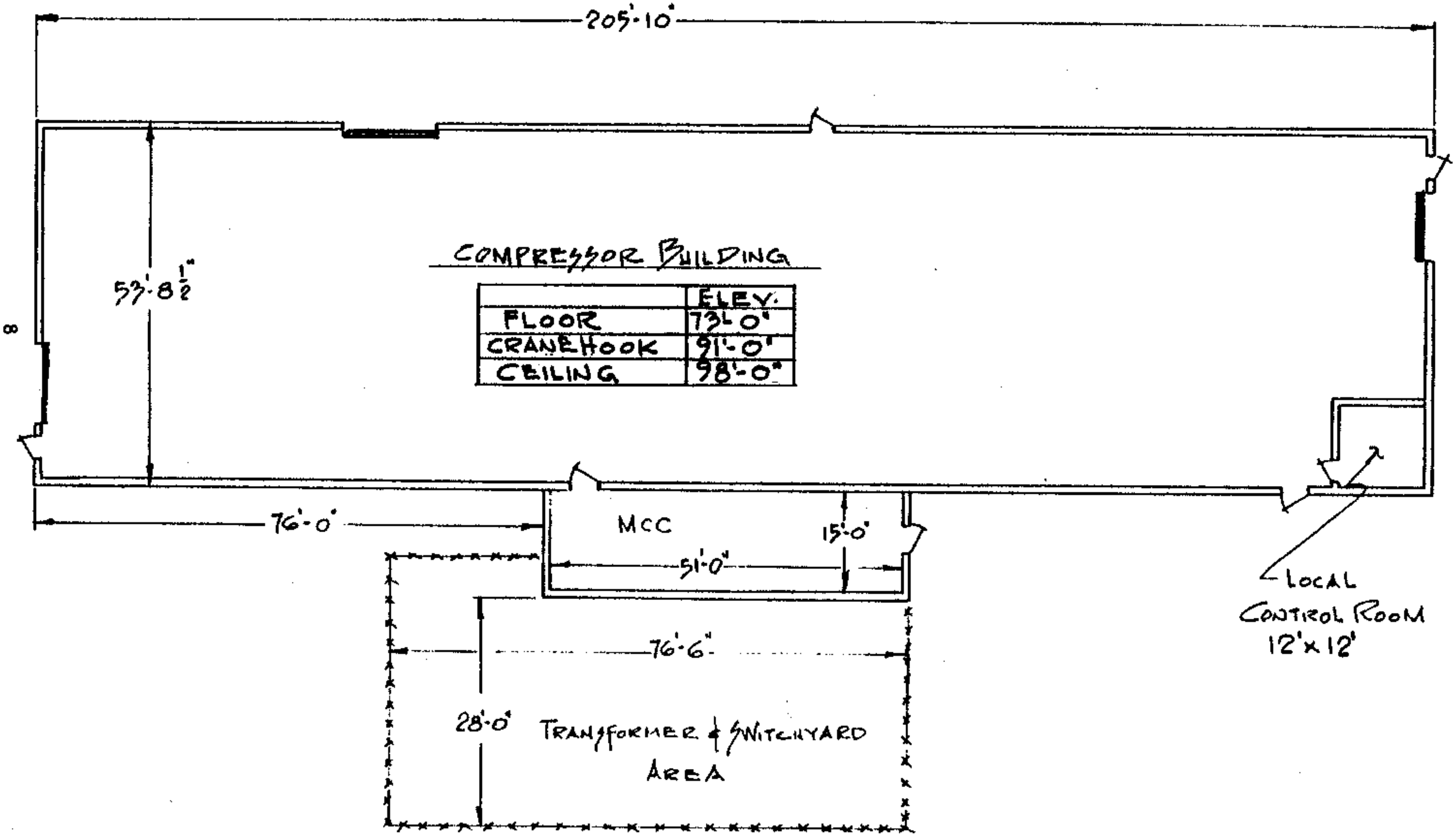


Figure 2-4
Compressor Building Plan

2. 3'-4" x 7'-2" hollow metal door on the west side at the northwest corner.

3. 3'-4" x 7'-2" hollow metal door on the south side at the southeast corner.

B. Helium Compressor Building exits are as follows:

1. 3'-4" x 7'-2" hollow metal door and adjacent 10' x 10' roll-up door on the east side at the northeast corner.

2. 3'-4" x 7'-2" hollow metal door and adjacent 12' x 14' roll-up door on the west side at the southwest corner.

3. 3'-4" x 7'-2" hollow metal door on north wall, approximately 90 feet from the west end.

4. 3'-4" x 7'-2" hollow metal door on south wall, approximately 20 feet from the east end.

5. 12' x 14' roll-up door on north wall, approximately 150 feet from the east end.

2.2.0 Utilities

2.2.1 Heating

Heating for the Cryogenic Building is accomplished through the use of 3 thermostatically controlled overhead steam unit heaters. Two 1700 CFM units are located over the floor space and one 750 CFM unit is over the roll-up door.

Heating for the Helium Compressor Building is accomplished through the use of five thermostatically controlled overhead electric unit heaters. Three 2500 CFM units are located over the floor space and 1250 CFM units are located over the east end and the west end roll-up door.

2.2.2 Ventilation and Emergency Exhaust System

In the Cryogenic Building both ventilation and emergency exhaust are provided by two 25000 CFM fans operated by a space thermostat ("Hand/Off/Automatic" Switch). Fan control switches are located at each personnel exit door and in the Control Room. The building volume is 240,000 cubic feet so there is an air change every 4.8 minutes when the fans are operating.

In the Helium Compressor Building both ventilation and emergency exhaust are provided by four 25000 CFM fans operated by a space thermostat ("Hand/Off/Automatic" Switch). Two 12500 CFM sound attenuators are provided for each fan. Fan control switches are located at each personnel exit door and in the Control Area. The building volume is 260,000 cubic feet, so there is an air change every 2.6 minutes when the fans are operating.

2.2.3 Electrical Distribution

In the Helium Compressor Building two 12000 kVA substations, 13.8 kV to 4160 volts supply power for the helium compressors. The building is serviced by one 1500 kVA substation, 13.8 kV to 480 volts.

The Cryogenic Building is serviced by one 2500 kVa substation, 13.8 kV to 480 volts.

All control instrumentation is fused and properly grounded. The three-phase wye-connected loads are powered through properly sized fused disconnects.

Emergency (battery powered) lights will illuminate stairways and exits in case of power outages.

2.2.4 Water Distribution

Domestic and fire protection water in each building is furnished by a combination 8-inch ductile iron water line extension from the 10-inch ductile iron water main loop adjacent to the Perimeter Road.

2.2.5 Fire Detection and Protection

Fire detection in each building is furnished by use of rate of rise thermal detectors.

Fire protection in each building is furnished by a wet pipe sprinkler system.

2.3 Cryogenic Facility

The cryogenic hardware for the 24.8 kW refrigerator and compressor facilities is being supplied and installed by Koch Process Systems (KPS), Westborough, Mass. according to BNL specifications. Only the control computer and some minor items are supplied by BNL.

A Block Diagram for the system designed by BNL is shown in Figure 2-5. Until magnets are installed in the tunnel, the refrigerator will only be run in a test mode (see Figure 2-6) in which the load is provided by electric heaters (calorimeters) and air-to-gas heat exchangers. These are provided as part of the supply by Koch. The calorimeters are built into the refrigerator cold boxes and the heat exchanger will be located out-of-doors.

The cryogenic plant is divided mechanically into two major segments, the refrigerator and the compressors. The control of these two segments is by a central computer in order to ensure that they run in concert.

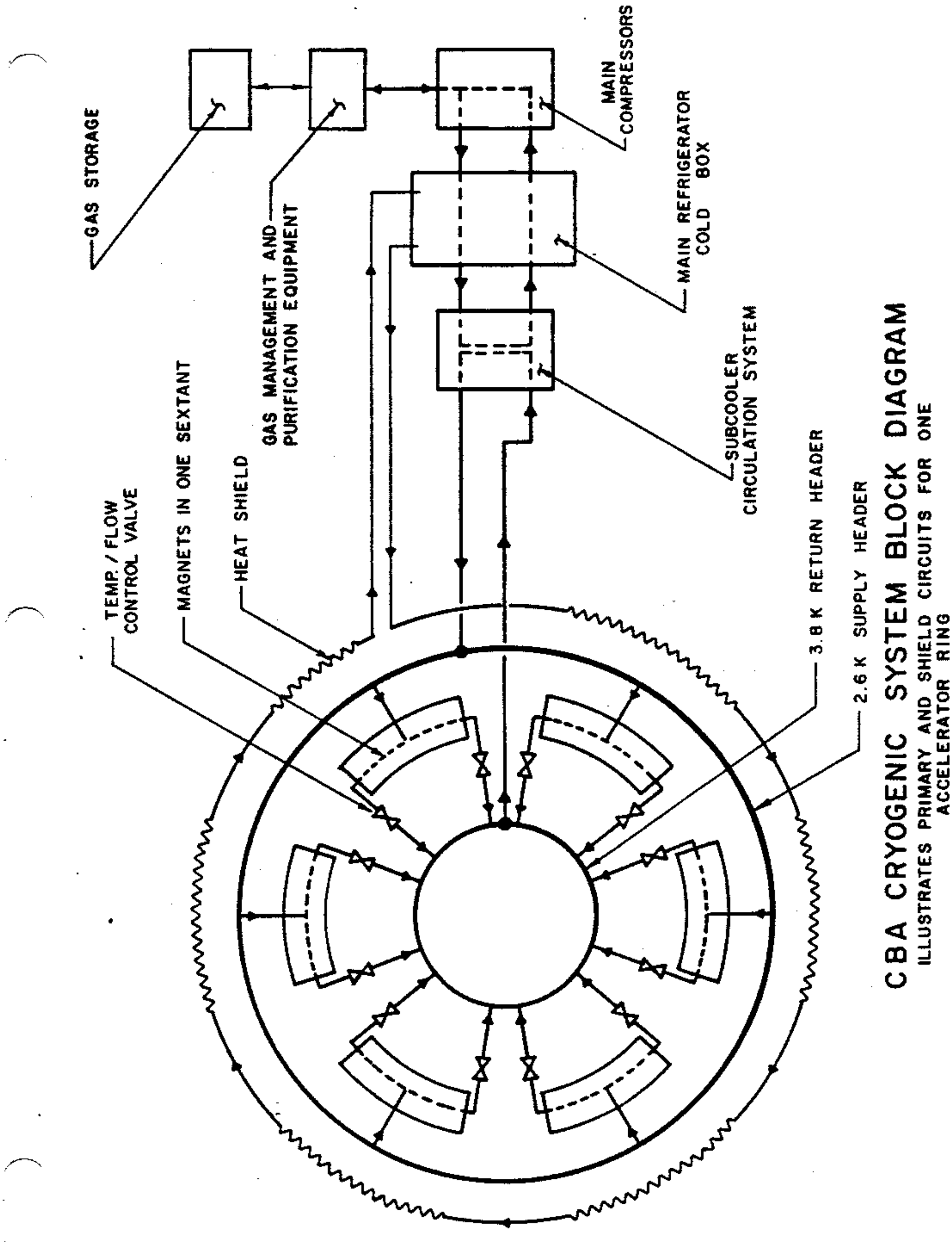

GAS STORAGE
GAS MANAGEMENT AND PURIFICATION EQUIPMENT
MAIN COMPRESSORS
MAIN REFRIGERATOR COLD BOX
SUBCOOLER CIRCULATION SYSTEM
TEMP. / FLOW CONTROL VALVE
MAGNETS IN ONE SEXTANT
HEAT SHIELD
3.8 K RETURN HEADER
2.6 K SUPPLY HEADER
CBA CRYOGENIC SYSTEM BLOCK DIAGRAM
ILLUSTRATES PRIMARY AND SHIELD CIRCUITS FOR ONE ACCELERATOR RING

Figure 2-5

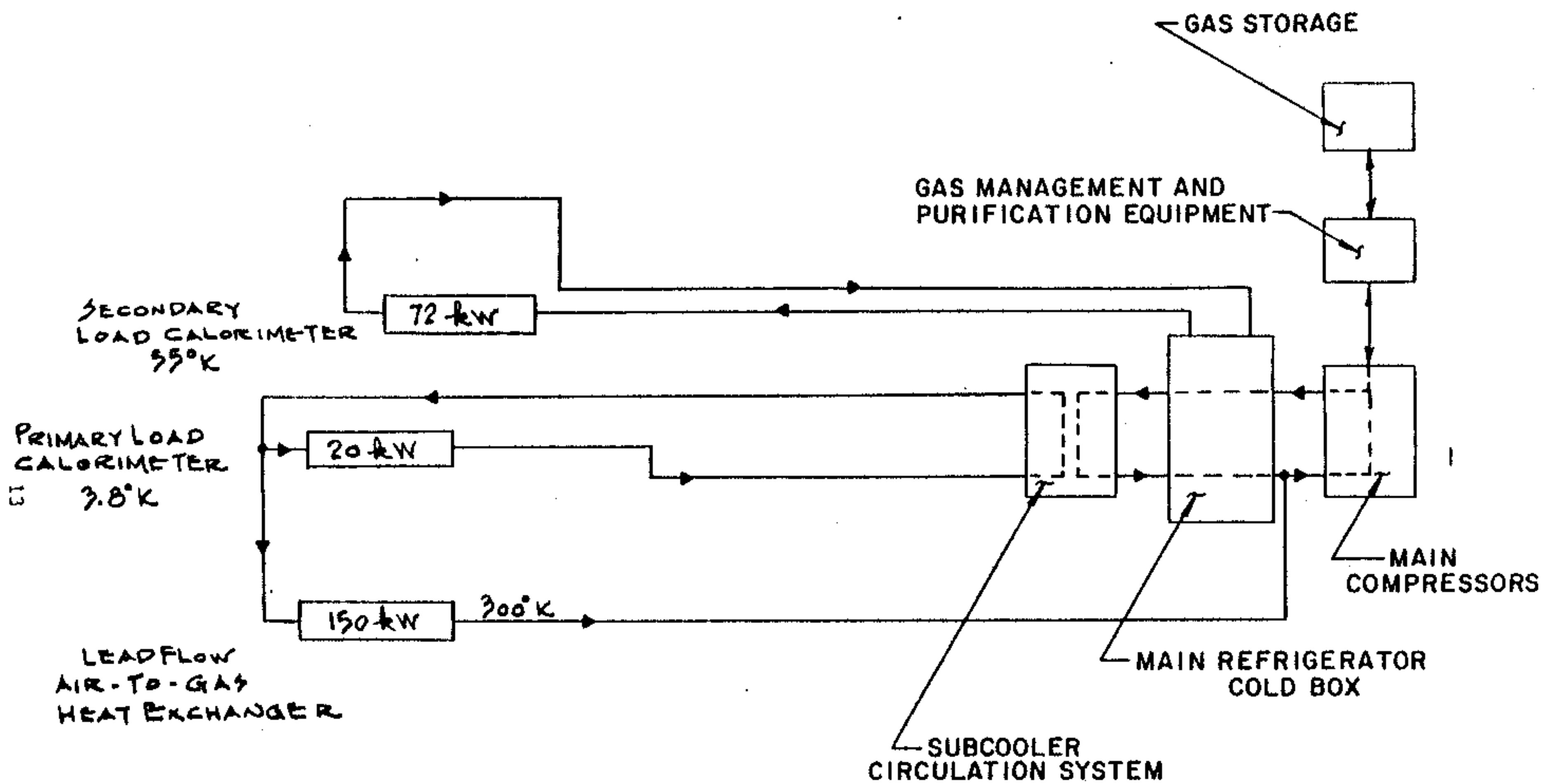


Figure 2-6
CRYOGENIC SYSTEM
ACCEPTANCE TEST CONFIGURATION

2.3.1 Compressor Section

2.3.1.1 General

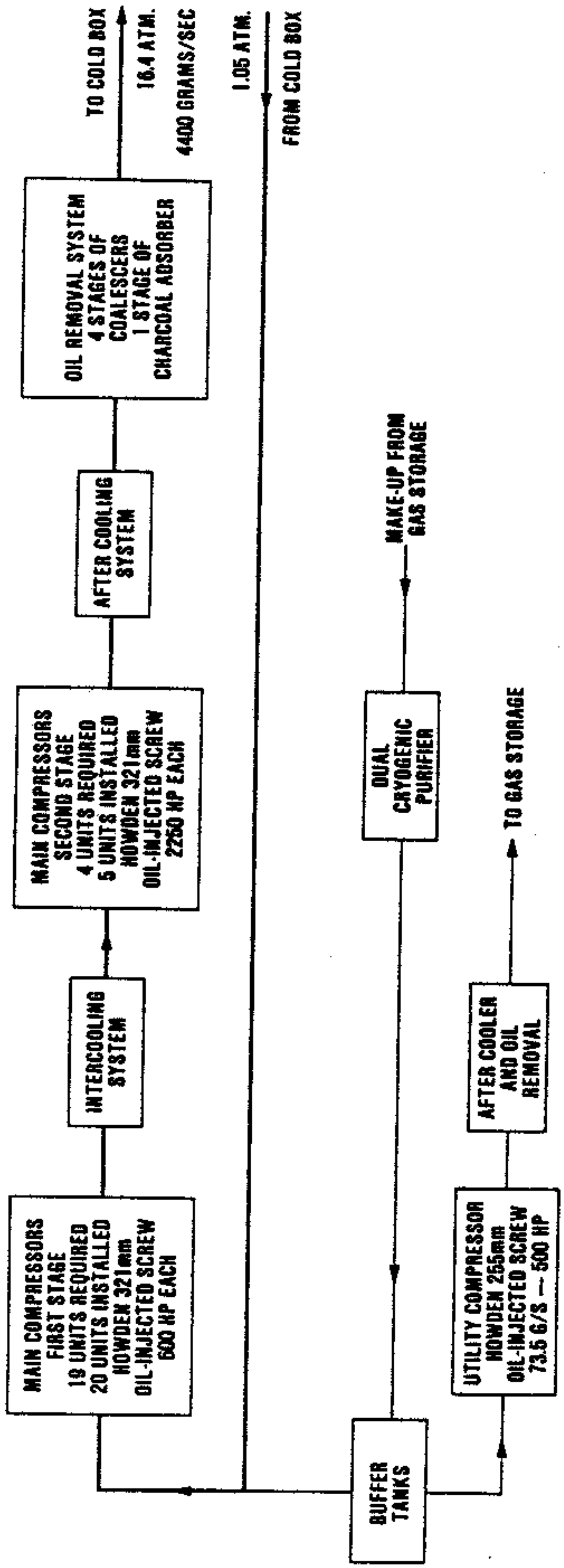
The helium compressor system is composed of several major elements. Included are twenty-six helium compressors, intercoolers, aftercoolers, oil removal system, vacuum pumps, buffer tanks, cryogenic purifier and instrument gas compressor. Figure 2-7 shows many of the various major elements in the system.

Figure 2-8 shows the location of the major system components in and around the compressor building. First stage compressor skids are aligned along the north and south walls beginning at the east end of the building. The second stage compressors are located along the north wall in the west part of the building. The purifier is located in the northwest corner of the building. The computer control room and gas management panels are in the southeast corner. Utility compressor, vacuum skids, redundant compressor intercoolers and aftercoolers are located along the western portion of the south wall. Motor control centers and control panel are located in the building addition located on the south wall. Buffer tanks are located outside along the building's north wall. Final oil removal equipment and the oil management systems are located outside by the southeast corner of the building.

2.3.1.2 Main Compressor

Two stages of compression are used to compress the helium required for the refrigerator. Oil-flooded rotary screw compressors are used in both stages.

The first stage screw compressors are mounted two on a skid with their motors, and a bulk oil separator, circulating lube oil system, piping and controls. Each compressor skid is a self-contained system capable of



COMPRESSOR SYSTEM BLOCK DIAGRAM

Figure 2-7

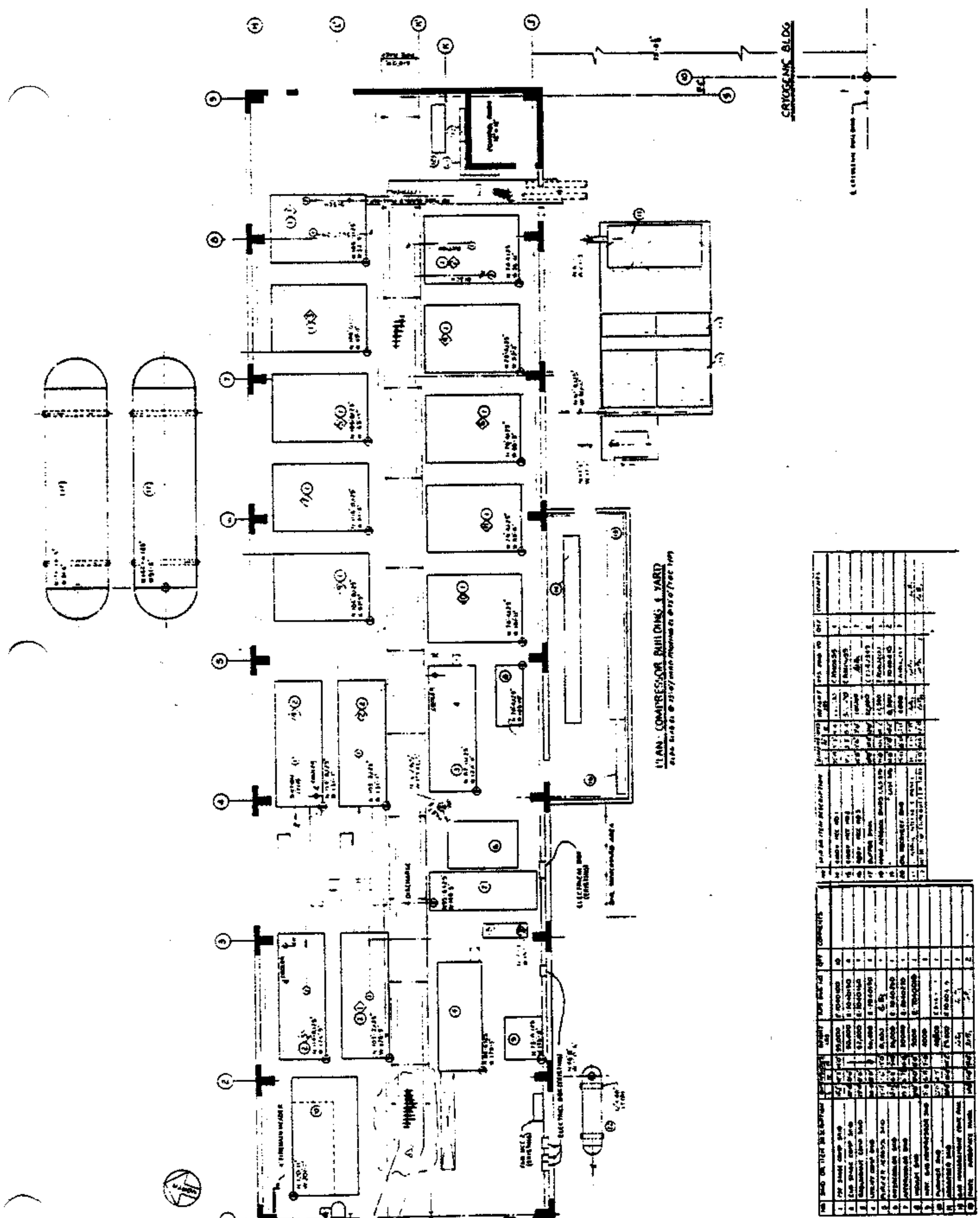


Figure 2-8
Compressor Room
Equipment Location

operating by itself and it is not dependent upon the operation of components on any other compressor skid. This modular approach simplifies start-up and provides efficient turn-down capabilities by operating only those compressors needed.

The second compression stage is comprised of four screw compressors operating in parallel. The second stage compressors are connected by a common suction manifold and a common discharge manifold. The second stage discharge stream proceeds to the aftercooler heat exchangers. Four water-cooled shell and tube heat exchangers cool the helium stream prior to entering the aerosol oil removal coalescers, oil vapor charcoal adsorbers and final particulate removal filters. The second stage screw compressors are individually mounted with each skid containing its compressor, 2250 HP motor, bulk oil separator, circulating lube oil system, oil cooler heat exchanger, piping and controls.

Redundancy of the compressor skid components is provided by a separate complete compressor skid capable of replacing a first or second stage compressor. The redundant compressor skid configuration is similar to that of the second stage compressor skid.

The four intercooler heat exchangers are mounted on a single skid with factory-installed isolation valves, interconnecting skid piping and instrumentation. The aftercooler heat exchanger skid is arranged in the same manner as the intercooler heat exchanger skid.

2.3.1.3 Oil Removal

Bulk oil separators are located at the discharge of each compressor. A combination of gravity separation, demister pads, and coalescing filter reduce oil content to less than 200 ppm in the helium gas exiting from the bulk separators, and minimizes oil return requirements.

Four stages of coalescing filters, in series, remove entrained oil droplets from the helium stream exiting the aftercoolers. Oil vapor that may remain in the helium is subsequently removed in a charcoal adsorber bed following the final coalescing filter. The clean high-pressure helium stream leaving the charcoal bed then passes through final particulate removal filters and proceeds to the cold box.

Redundancy is provided by organizing the coalescers, charcoal adsorbers, and particulate filters into three half-capacity trains. Any two trains can be on line, with the third in standby.

2.3.1.4 Gas Management

The gas management system is designed to efficiently accomplish evacuation, purge and backfill, startup and system cooldown, normal steady state system operation, system warmup, helium transfer, purification and storage, maintenance and repair.

Each major component in the Helium Compressor Station can be isolated for evacuation, purging and backfilling. Evacuation is accomplished by closing the component's isolation valves and opening the component's valve to the vacuum header. The Helium Compressor Station can be isolated from the cold box. Interconnecting piping, discharge and suction headers can be treated in the same manner as any other major component.

After the component has been evacuated, backfilling with helium can be done by opening the valve to the purge header. Once the component has been been backfilled with helium, the cryogenic purifier can be used for final cleanup. A closed loop path from the isolated component to the cryogenic purifier, then to the utility compressor, then to the purge header and finally back to the component is provided. The main helium compressors can circulate by themselves or use the utility compressor for final cleanup through the purifier.

During the cold box cooldown, make-up gas will come from existing gas storage facilities to the cryogenic purifier. From the cryogenic purifier, the clean helium makeup enters the buffer tanks and finally enters the main compressor suction header.

The main helium compressor system can be operated independently from the cold box. Full-flow bypass lines are provided from the high pressure discharge header to the medium (interstage) pressure header and from the medium pressure header to the low pressure suction header. Pressure control valves and instrumentation are provided to allow stable automatic control of the header pressures.

The suction buffer tanks are horizontal pressure vessels, piped in parallel with each tank having its own isolation, purge and relief valves. Buffer tank headers are piped directly to the main compressor suction header. The buffer tanks can be evacuated, purged and cleaned in the same manner as any other major component in the system, and used for either storage or as a buffer volume.

2.3.1.5 Piping

Piping for the Helium Compressor Station is designed, fabricated and tested in accordance with ANSI B31.1 Power Piping requirements. All major piping was analyzed to the requirements of ANSI B31.3 Chemical Plant and Petroleum Refinery Piping requirements.

Interfaces between components and process piping are welded wherever possible. Flanged connections, where required, use "O"-ring seals.

All piping subject to thermal cycling has been stress-analyzed. A detailed finite element analysis of pressure, dead weight, thermal and vibration stresses has been done with particular attention given to piping connected to the compressor casing.

2.3.1.6 Purifier

The cryogenic helium purifier is a self-contained skid-mounted system designed to purify 250 grams per second of helium. The purifier utilizes coalescing filters to remove oil droplets in the influent helium stream. Large capacity dual plate fin heat exchangers freeze-out water vapor as the helium is cooled. The helium is further cooled in two more plate fin heat exchangers. The helium then enters one of the dual, liquid nitrogen-cooled charcoal adsorbers where any air or nitrogen is removed. The clean helium stream is then warmed up in the plate fin heat exchangers and returned to the main process stream.

2.3.1.7 Utility Compressors

The utility compressor is an oil-flooded rotary screw compressor which operates in conjunction with, or independently from the main helium compressors. The utility compressor is skid-mounted and has its own dedicated circulating lube oil system and oil clean-up system. The aerosol oil removal system has four stages of coalescing filters, a charcoal bed to adsorb oil vapor, and a final particulate filter.

The instrument gas compressor is also an oil-flooded rotary screw compressor. The instrument gas compressor is skid-mounted and has its own lube oil system and instrumentation and controls for unattended operation. The instrument gas compressor is supplied with nitrogen gas from the cryogenic purifier boiloff or from the nitrogen dewar vaporizer. The instrument gas compressor supplies gas to meet all pneumatic requirements of the Cryogenic System in the Cryogenic and Compressor Buildings.

2.3.1.8 Vacuum Pumps

Three vacuum pump skids are provided to meet the vacuum requirements of the Helium Compressor Station. Each skid has a single vacuum pump with all piping, instruments and controls required for proper operation. The exhaust from the pumps is piped outside of the building. The vacuum pump skids are manifolded in parallel such that each pump can be used in place of any other pump. One vacuum pump skid will normally be reserved for the reactivation procedures of the cryogenic purifier system.

2.3.2 Cold Box Section

2.3.2.1 General Description

The refrigerator system utilizes the Claude cycle, without liquid nitrogen precooling, to simultaneously supply the following refrigeration capacities:

1. 55,000 watts at 15 ATM and 40 K supply to the load shield circuit with a 9.7 ATM and 69.5 K return conditon.

2. A primary load mass flow of 4154 g/s of supercritical helium at 2.59 K and accepting 4054 g/s return flow at 4.19 K.

3. A mass flow of 100 g/s removed from the primary load circuit for electrical lead and other cooling loads and returned to compressor suction, at near ambient conditions.

2.3.2.2 Physical Arrangement

The cold box section of the refrigerator is comprised of heat exchangers, piping, dual impurity adsorption equipment, turbine expanders and turbine compressor. See Figure 2-9 which is a Block Diagram showing the arrangement of this equipment.

This equipment, since it all operates at low temperatures, is housed within vacuum tanks or casings. A single exception is the low temperature piping interconnecting components of the refrigerator. The warmer sections of these lines, with a design condition from ambient temperature to 80 K are insulated with closed cell foam insulation with a vapor barrier. Below this temperature the lines are vacuum insulated.

The heat exchangers, interconnecting piping and valves are contained within cold boxes (vacuum tanks) 1 to 5. These tanks are outside the Cryogenic Building at grade elevation (73 ft above MS). They are mounted in saddles and supported by concrete footings. One end of each tank projects through the wall into the building. Cold boxes 1 and 2 are the warm end of the refrigerator and are located to the west side of the Cryogenic Building, nearest the Compressor Station. Cold box 5 is to the east and houses the coldest components.

The refrigerator assembly is arranged within the Cryogenic Building in such a way that the process components, cold boxes, turbine pods and most low temperature piping are on the 73 ft. elevation (Mezzanine). Also located on this level is the refrigerator control room. Figures 2-10A and 2-10B are plan views showing the location of major components.

The lower floor (63 ft. elev.) contains ancillary equipment for the insulating vacuum vessels and the turbine machinery.

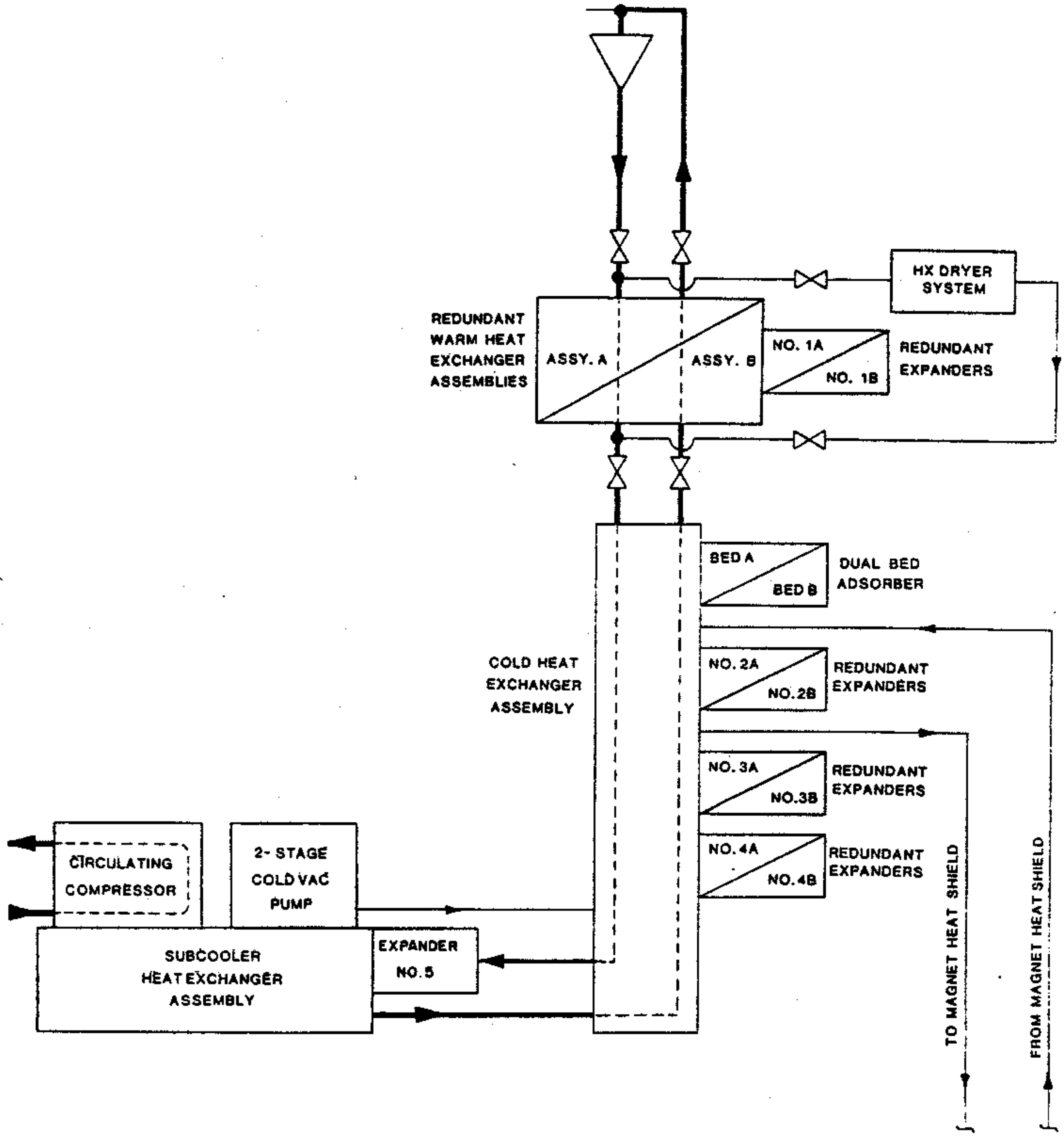


Figure 2-9
Refrigerator Block Diagram

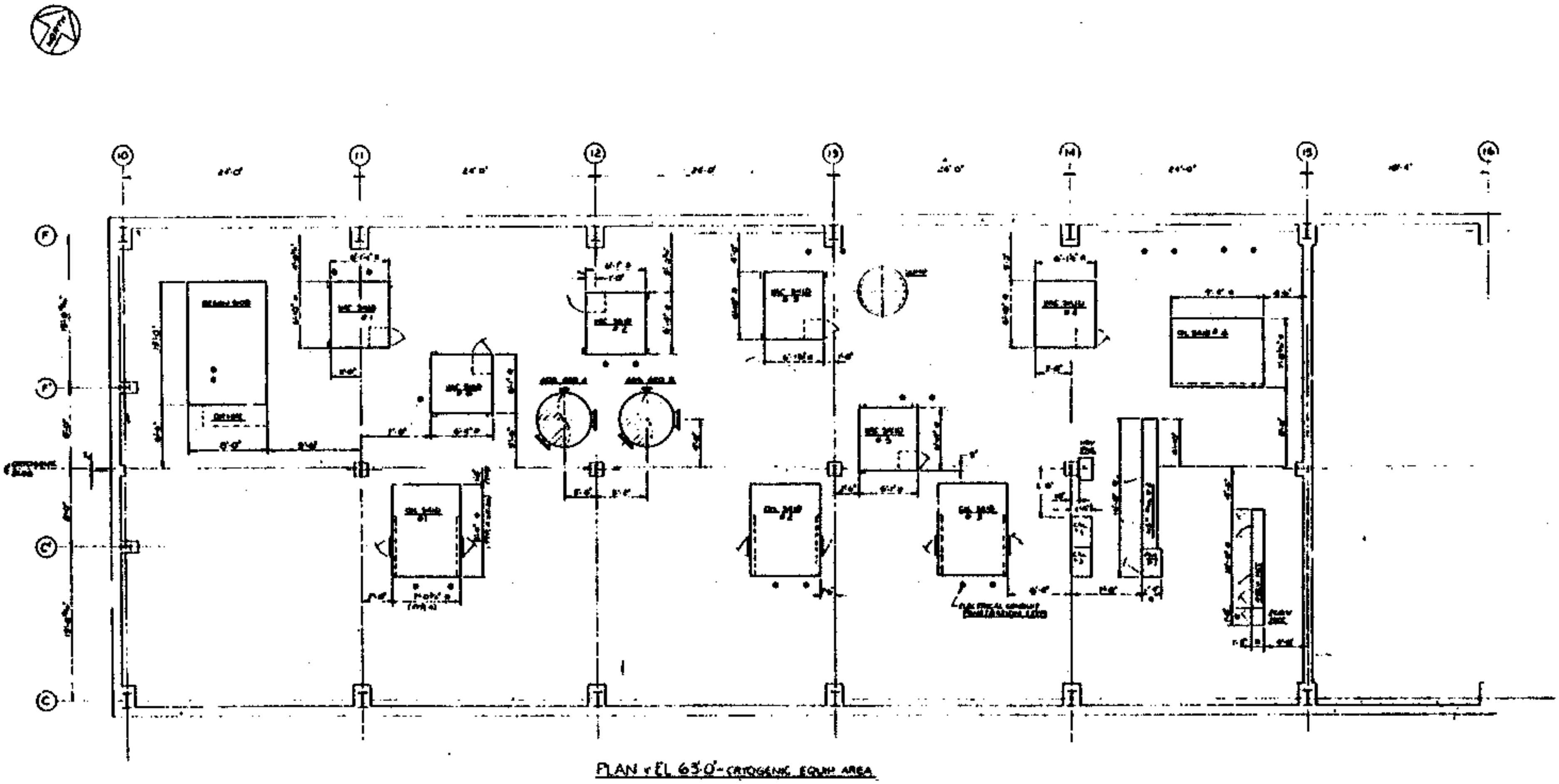


Figure 2-10A
Cryogenic Building Equipment Location
Elevation 63'

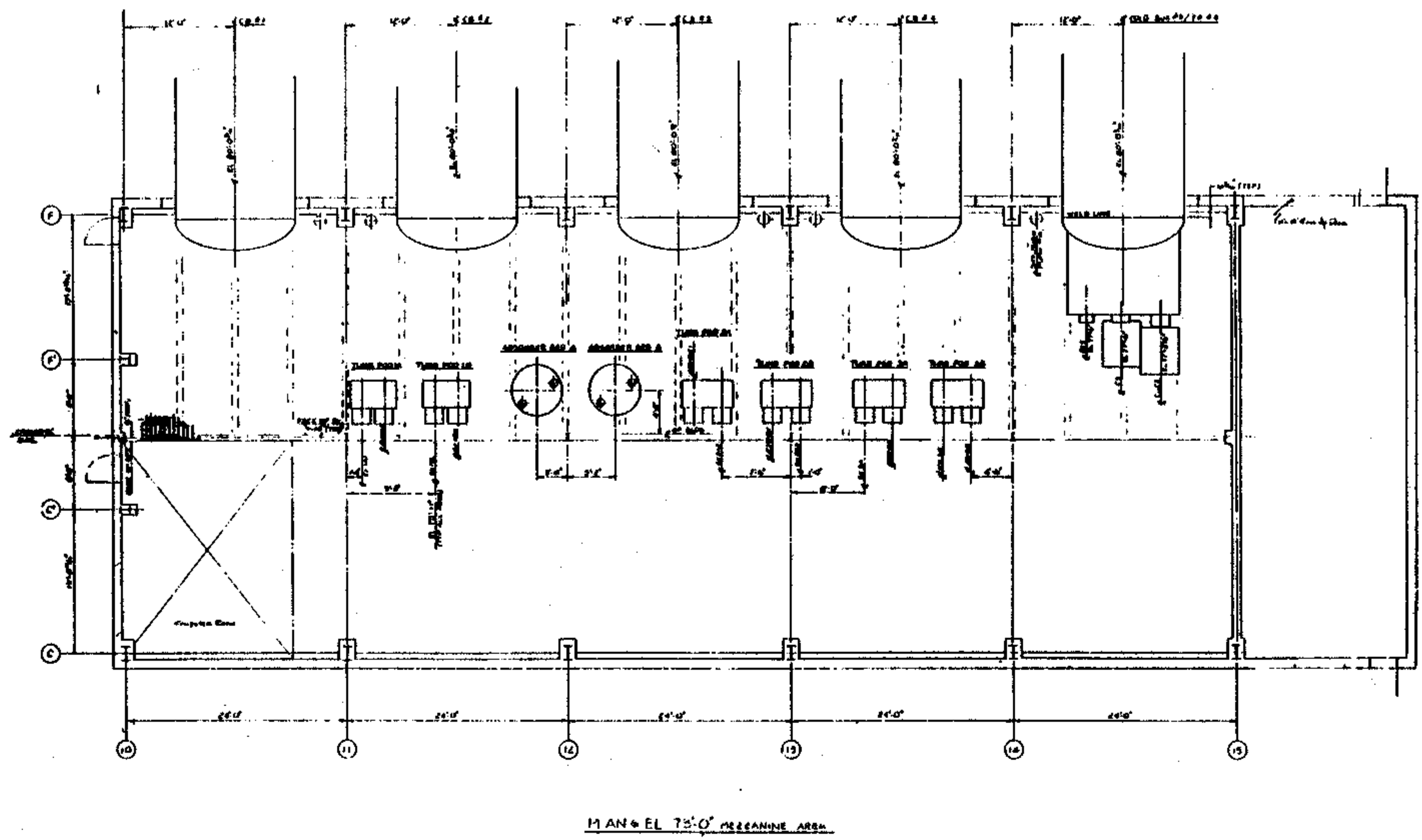


Figure 2-10B
Cryogenic Building Equipment
Location - Elevation 73'

Subsystems such as the electrical distribution and control, heat exchanger and adsorber regeneration equipment, cooling water and the like are also located at this level.

The pair of cryogenic adsorbers are mounted at this level and project through the mezzanine floor. Process piping connections are above the 73' elevation.

2.3.2.3 <u>Brief Description of Refrigeration Cycle</u>

The refrigerator can be considered to be in two sections (see Figures 2-11 and 2-12):

1. The main refrigerator which produces liquid helium boiling at slightly above atmospheric pressure at 4.61 K.

2. The subcooler section which maintains three liquid helium baths boiling at atmospheric and subatmospheric pressures at 4.61 K, 3.27 K and 2.49 K are known as the high pot (HX 10), intermediate pot (HX 11 and 12), and low pot (HX 13), respectively.

This section also contains the internal portion of the load circuit. This circuit provides a high mass flow of supercritical helium to the load and return.

High pressure (HP) ambient temperature helium gas enters the refrigerator from the compressor station. Simultaneously low pressure (LP), ambient temperature gas leaves the refrigerator for the compressor station to be recompressed and returned to the refrigeration cycle.

The HP gas is cooled in the main refrigerator by heat exchange with cold LP gas being warmed to return to the compressor station. The source of the LP gas is: 1) vapor from the subcooler section liquid pots and, 2) from the discharge of five sets of turbine expanders operating at different

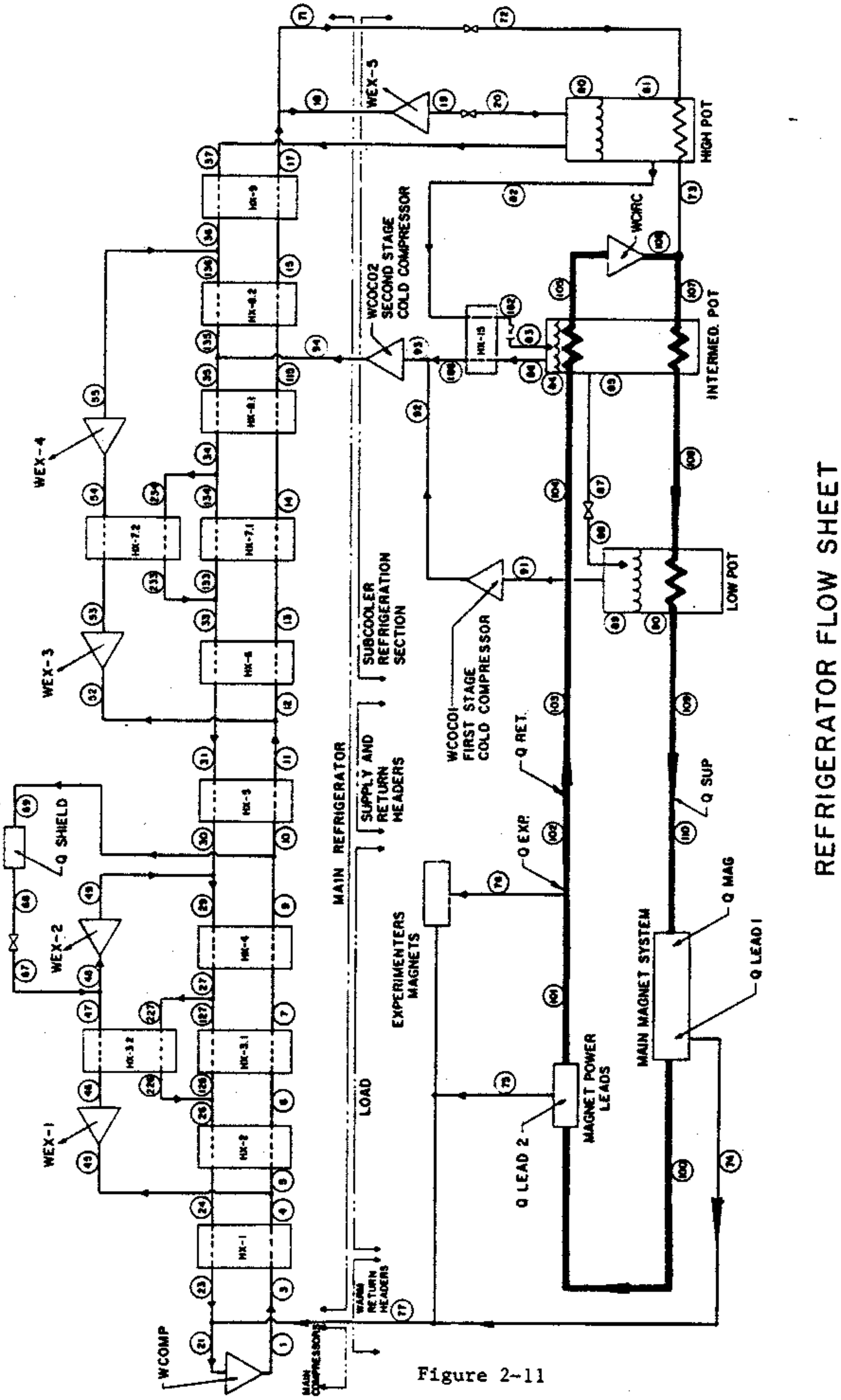

REFRIGERATOR FLOW SHEET
WCOMP
MAIN COMPRESSORS
WARM RETURN HEADERS
LOAD
MAIN REFRIGERATOR
SUPPLY AND RETURN HEADERS
SUBCOOLER REFRIGERATION SECTION
WEX-1
WEX-2
WEX-3
WEX-4
WEX-5
HEAT SHIELD
Q SHIELD
EXPERIMENTERS MAGNETS
MAGNET POWER LEADS
MAIN MAGNET SYSTEM
Q LEAD 2
Q LEAD 1
Q MAG
Q EXP.
Q RET.
Q SUP
WCOCO1 FIRST STAGE COLD COMPRESSOR
WCOCO2 SECOND STAGE COLD COMPRESSOR
WCRC
LOW POT
INTERMED. POT
HIGH POT

Figure 2-11

PROGRAM 15A62

CALCULATED PERFORMANCE OF A HELIUM REFRIGERATOR WHICH UTILIZES 5 EXPANDERS AND 3 COLD COMPRESSORS. DELIVERY OF THE REFRIGERANT IS IN THE FORM OF COMPRESSED LIQUID HELIUM WHICH IS CIRCULATED BY ONE OF THE THREE COMPRESSORS IN THE CYCLE.

SUMMARY OF SYSTEM PARAMETERS

SYSTEM DESIGN STEADY-STATE LOAD REQUIREMENTS

REFRIGERATION REQUIRED-WATTS							MASS FLOW REQUIRED-GM/SEC		
QMAG	QLEAD1	QLEAD2	QSUP	QRET	QEXP	QSHLD	F74	F75	F76
7650.	200.	2300.	1500.	2000.	0.	56000.	6.	44.	50.

OTHER ESTIMATED REFRIGERATION LOADS-WATTS

QHX1	QHX2	QHX3	QHX4	QHX5	QHX6	QHX7	QHX8	QHX9	QHX10	QHX11	QHX12
947.0	3240.0	2663.0	1880.0	240.0	410.0	600.0	520.0	180.0	340.0	290.0	290.0

EXPANDER/COMPRESSOR PARAMETERS

	MAIN COMPR.	COLD COMPR. 1	COLD COMPR. 2	CIRC. COMPR.	EXPANDER 1	EXPANDER 2	EXPANDER 3	EXPANDER 4	EXPANDER 5
ADIABATIC EFFICIENCY		.660	.670	.580	.810	.820	.800	.780	.760
ISOTHERMAL EFFICIENCY	.60								
INLET PRESSURE-ATM	1.050	.095	.340	4.150	16.227	8.860	15.579	7.922	15.494
OUTLET PRESSURE-ATM	17.250	.350	1.388	5.450	9.000	1.301	8.000	1.423	2.500
INLET TEMPERATURE-K	302.00	2.48	4.61	3.47	185.00	89.37	25.00	12.38	6.29
OUTLET TEMPERATURE-K	305.00	4.83	9.64	3.78	153.64	38.93	20.18	7.10	5.14
FLOW RATE-GM/SEC	4212.2	333.2	982.4	4054.0	658.3	1014.2	1729.0	1729.0	1368.9
WORK-WATTS	12427821.	3933.	24784.	6213.	-108816.	-162034.	-42130.	-36738.	-10488.
WORK-HP	16658.	5.	33.	8.	-146.	-217.	-56.	-49.	-14.

HEAT EXCHANGER PARAMETERS

	HX1	HX2	HX3.1	HX3.2	HX4	HX5	HX6	HX7.1	HX7.2	HX8.1	HX8.2	HX9	HX15
EFFECTIVENESS	.976	.942	.978	.978	.964	.939	.973	.988	.986	.890	.954	.939	.923
NTU	26.43	8.71	29.05	25.89	12.83	10.22	6.26	17.67	17.59	1.75	5.64	3.00	5.16
AU(KW/K)	607.09	161.00	523.50	95.93	238.09	185.86	53.37	136.23	152.71	18.62	54.22	8.46	20.19

LOAD SUMMARY

	PRIMARY LOAD		SECONDARY LOAD	
	SUPPLY	RETURN	SUPPLY	RETURN
FLOW RATE-GM/SEC	4153.98	4053.98	355.91	355.91
TEMPERATURE-K	2.59	4.19	40.00	69.35
PRESSURE-ATM	5.35	4.20	15.67	9.67
DENSITY-GM/CC	.154	.138	.01642	.00668
ENTHALPY-J/GM	7.32	10.63	222.00	376.53

FLUID PROPERTIES AND FLOW RATES

PRESSURE(ATM), TEMPERATURE(K), ENTHALPY(J/GM) AND FLOW RATE(GM/SEC)

POINT	PRESS.	TEMP.	ENTHAL.	FLOW
1	17.250	305.00	1604.33	4212.15
3	16.400	305.00	1604.04	4212.15
4	16.278	185.00	980.61	4212.15
5	16.278	185.00	980.61	3553.88
6	16.181	153.64	817.52	3553.88
7	15.898	89.37	377.82	3553.88
9	15.878	40.00	222.00	3553.88
10	15.666	40.00	222.00	3197.97
11	15.636	25.00	139.41	3197.97
12	15.636	25.00	139.41	1468.94
13	15.606	20.18	111.54	1468.94
14	15.575	12.38	62.75	1468.94
115	15.558	10.45	48.84	1468.94
15	15.543	7.30	28.27	1468.94
17	15.533	6.28	23.58	1468.94
18	15.494	6.28	23.58	1368.94
19	2.500	5.14	15.93	1368.94
20	1.434	4.61	15.93	1368.94
LIQUID FRACTION AT PT. 20 IS .775				
80	1.424	4.61	29.54	386.50
81	1.424	4.61	11.98	1061.35
82	1.424	4.61	11.99	982.44
182	1.414	3.47	7.07	982.44
83	.350	3.27	7.07	982.44
LIQUID FRACTION AT PT. 83 IS .953				
84	.350	3.27	29.03	649.21
85	.350	3.27	5.98	836.41
86	.350	3.27	29.03	649.21
186	.340	4.49	36.47	649.21
87	.350	3.27	5.98	333.23
88	.100	2.49	5.99	333.23
LIQUID FRACTION AT PT. 88 IS .913				
89	.100	2.48	28.63	333.23
90	.100	2.49	4.02	304.15
91	.095	2.48	26.53	333.23
92	.350	4.83	38.33	333.23
93	.340	4.61	37.10	982.44
94	1.389	9.64	42.31	982.44

POINT	PRESS.	TEMP.	ENTHAL.	FLOW
21	1.050	302.00	1583.34	4212.15
23	1.100	302.00	1583.34	4112.15
24	1.139	178.89	944.52	4112.15
26	1.166	151.69	802.78	4112.15
126	1.166	151.69	802.78	3468.61
127	1.243	84.90	351.89	3468.61
226	1.166	151.69	802.78	643.54
227	1.243	84.90	351.89	643.54
27	1.243	84.90	351.89	4112.15
29	1.294	38.93	216.76	4112.15
30	1.306	38.93	216.76	3097.97
31	1.318	22.60	131.43	3097.97
33	1.330	20.06	116.06	3097.97
133	1.330	20.06	116.06	1468.38
134	1.348	10.87	69.07	1468.38
233	1.330	20.06	116.06	1629.58
234	1.348	10.87	69.07	1629.58
34	1.348	10.87	69.07	3097.97
35	1.389	9.64	62.31	3097.97
135	1.389	9.64	62.31	2115.53
136	1.404	7.10	47.78	2115.53
36	1.404	7.10	47.78	386.50
37	1.411	4.60	29.54	386.50
100	4.550	3.80	9.57	4147.98
101	4.550	3.99	10.13	4103.98
102	4.550	3.99	10.13	4053.98
103	4.200	4.19	10.63	4053.98
104	4.200	4.19	10.63	4053.98
105	4.150	3.47	8.47	4053.98
106	5.450	3.78	10.01	4053.98
107	5.450	3.82	10.08	4153.98
108	5.400	3.37	8.91	4153.98
109	5.350	2.59	7.32	4153.98
110	5.000	2.60	7.66	4153.98

POINT	PRESS.	TEMP.	ENTHAL.	FLOW
45	16.227	185.00	980.61	658.27
46	9.000	153.64	815.31	658.27
47	8.904	89.37	376.53	658.27
48	8.860	89.37	376.53	1014.18
49	1.301	38.93	216.76	1014.18
52	15.579	25.00	139.41	1729.03
53	8.000	20.18	115.06	1729.03
54	7.922	12.38	69.03	1729.03
55	1.423	7.10	47.76	1729.03
67	8.904	69.37	376.53	355.91
68	9.666	69.35	376.53	355.91
69	15.666	40.00	222.00	355.91
71	15.494	6.29	23.58	100.00
72	5.550	6.34	23.58	100.00
73	5.450	4.71	13.14	100.00
74	4.875	3.35	8.63	6.00
75	4.550	3.80	9.57	44.00
76	4.550	3.99	10.13	50.00
77	1.050	302.00	1583.32	100.00

Figure 2-12

temperatures in the cycle, i.e., into expander 1 (two stages - 1A1 and 1A2) at 185 K, into expander 2 at 69 K, into expander 3 at 25 K, into expander 4 at 12 K and into expander 5 at 6.3 K.

The output of expander 5 undergoes a Joule/Thompson expansion which results in the production of two-phase helium (about 78% liquid) at 4.61 K being delivered to the subcooler section HX 10.

Of the total ambient temperature HP gas delivered to the refrigerator, about 35% is involved in expansion through expander 5 and the Joule/Thompson process. The bulk (65%) had been extracted for passage through the aforementioned turbine expanders.

The function of the turbine expanders is to cause the helium gas to perform mechanical work and thereby extract energy from the gas. The discharge from the turbine expanders, now at a lower temperature and pressure becomes the major part of the return LP flow used to cool the inbound HP flow.

The mechanical power extracted is delivered to the atmosphere at the cooling towers via a turbine oil loop and then via heat exchangers to the cooling water system.

The subcooler section of the refrigerator provides for the circulation of the 5 atm primary mass flow to the load and for cooling of the return flow from the load. This is accomplished by a high mass flow, low boost pressure turbocirculator operating at load temperatures. Heat energy absorbed into this load flow from magnets, cryostats, piping and turbocirculator and other components is transferred to the main refrigeration section via heat exchange into baths of liquid helium boiling at subatmospheric pressures. P&I Figure 2-11 delineates the route. The liquid in the intermediate pot is boiling at 3.27 K (0.35 atm). The liquid in the low pot is boiling at 2.49 K (0.1 atm). The properties of the flow to the load are 2.59 K, 5.35 atm with a total mass flow of 4154 g/s. The return flow is at 4.2 K, 4.2 atm and 4054 g/s.

The vapor pressure in the intermediate pot is sustained by two stages of compression and the low pot by four stages of compression. The impellers for all four stages of compression are mounted on a common turbocompressor shaft. The first compressor section transports the product from the low pot (333 g/s) to the pressure of the intermediate pot. The second compressor section transports the product from both the low and intermediate pot (333 + 649 = 982 g/s) to the pressure of the refrigerator return.

A 355 g/s HP flow, which is part of the feed to turbine expander 2 is first sent to the external load shield at 15.7 atm and 40 K. This gas is approximately at 9 atm and 69 K upon return from the shield.

The turbine expanders 1 to 4 are provided in redundant pairs. This is for two reasons. The first being that malfunctions resulting in downtime are most likely to be mechanical in nature. The second reason is that the time required to cool the refrigerator and load from ambient to operating conditions is considerably less when using both pairs of all expanders.

Expander 5, which is not redundant, is a small and simple unit which can be isolated from the cycle, warmed up if necessary, repairs effected, components replaced, and be returned to service in a short time, with only a modest warming and with no loss of helium mass from the load circuit, albeit, with the accelerator magnets unpowered during this period.

Heat exchangers No. 1 and No. 2 are also provided in redundant pairs with HX 1A and 2A occupying cold box 1 and HX 1B and 2B in cold box 2.

These parallel pairs of exchangers are to allow periodic warming of one section during continuous operation, for the purpose of deriming impurities from heat exchanger surfaces.

Dual, full flow adsorber beds operating at low temperature for continuous adsorption of oxygen and nitrogen and a regeneration system for adsorber cleanup, are also part of the refrigerator.

A small fraction of the load flow fluid (100 g/s) is extracted at the load to provide cooling for the magnet electrical leads. This gas is warmed to ambient conditions in the process and is returned directly to the Compressor Station. Make-up gas to the load loop is provided by the main refrigerator via the high pot exchanger HX 10.

Three calorimeters are part of the refrigerator. Two of these are electrical resistance heaters in contact with the process gas. One is in the shield load circuit, the second is in the primary load circuit. Both are sized to simulate the full heat load of the circuit. Both are piped in a series/parallel arrangement to supplement a small external load or totally substitute for an external load. They can also be used to measure the refrigerator's capacity during diagnostics.

The third calorimeter substitutes for the lead flow extraction of 100 g/s when no external load exists.

Refrigerator Circuit Design Pressures.

1.	HP circuit heat exchangers, piping, turbines adsorbers, flow meters	- 20 atm
2.	Medium pressure circuits (between expander sets)	- 20 atm
3.	LP circuits	- 5.4 atm
4.	LP circuits (heat exchangers)	- 6.8 atm

5. Load circuit heat exchangers, piping turbo-compressors - 20 atm

6. Subcooler liquid pots - 20 atm

Along with other requirements imposed on the designer/fabricator, the pressure vessels conform to the "ASME Boiler and Pressure Vessel Code, Section VIII - Unfired Pressure Vessels". The piping conforms to "Code for Pressure Piping, ANS1 B31.3, Petroleum Refinery Piping".

2.3.2.4 Vacuum Vessels

A. Cold Boxes - Five horizontal cylindrical vacuum tanks are employed, four of which house and provide the thermal insulation for the main refrigerator heat exchangers, valves and piping.

The fifth tank, the subcooler section, contains the liquid helium pots and associated heat exchangers. Tank five (cold box 5) has turbo pod which is mounted integral with the indoor end cap. The insulating vacuum is common to both tank and pod.

Each vacuum vessel is designed to meet all requirements of the ASME Code for Unfired Pressure Vessels Section VIII, Division 1, for cylindrical vessels under external presure. The vessels are designed to meet 10 psig internal and 15 psig external pressure at 100°F internal and external temperature. These vessels are not ASME code stamped since the maximum design operating pressure differential does not exceed 15 psi. All vessels (cold box 5 has two) are equipped with a 10-inch captive plate type relief valve which opens (2.125-inch lift) as soon as the internal pressure goes positive. The relief valve, when the internal tank pressure reaches 10 psig, is sized to vent off the largest contained process fluid flow available should a line rupture. These relief valves are located on the out-of-doors section of the vacuum tanks.

A cap will prevent rain and snow from reaching these relief valves and causing a malfunction.

The maximum compressor flow rate (4400 g/s) is taken as the maximum venting rate in the first four cold boxes. Because of the stored liquid in the pots of cold box 5, it is necessary to design for a higher venting rate and two vent valves are provided which have a combined flow capability in excess of 10,000 g/s with the design 10 psi pressure drop.

These vessels have an internal diameter of 13 feet and are of two lengths, 35 ft. O.A. for cold boxes 1, 2 and 4 and 45 ft. for cold boxes 3 and 5. They are of welded carbon steel construction, the shells being rolled from 3/8" plate, SA 515 grade 70. The end caps are ASME elliptical 2:1 (SPUN) fabricated from 7/16" thick, SA 285 Grade C steel. External reinforcing rings are employed on the shell. The vessels rest on two saddle type supports.

Two 30" ID hatchways are provided for entry and for ventilation, one being located on the end inside the building with the other outdoors mounted on the shell or end cap. The maintenance procedures will detail the procedures required before and during "occupancy" of these vacuum tanks for repairs and maintenance.

Portable ventilation fans exist that can be mounted on the hatch flanges. They are hinged to easily swing away from this opening when necessary.

No permanent internal lighting is used, instead portable strings of lights are available. Grab irons are mounted within the tanks where necessary for assistance in transiting the hatch.

Cold boxes 3, 4 and 5 are equipped with railed platforms on the tank tops. These are connected via spanning walkways and a stairway and ladder to grade elevation. Access is required to these tank tops for purposes of operating the manual valves and maintenance of automatic valves and other controls.

B. Adsorbers - The two vertical adsorber vacuum vessels are 5'-6" OD and are 16 feet tall. The design and material requirements are identical with the cold box requirements. The two access hatches provided in each vessel have a 20" ID opening.

C. Turbo Pods - The seven vacuum boxes which house the turboexpanders are of rectangular shape with external ribs. The material and design requirements are again similar to those already described. Access hatches of 18" size are located on either end of the box.

2.3.2.5 Cold Box Internal Piping

The process equipment contained within the five cold boxes consists of heat exchangers, valves, temperature sensors, flow measurement elements, pressure tap connections, both aluminum and stainless steel piping and transition joints for aluminum/stainless steel piping connections.

The heat exchangers are clustered in one or more assemblies. The frames supporting these clusters are hung from the vacuum vessel support rings by slender tension rods to minimize the heat leak into the process.

Piping routes between tank penetration nozzles, heat exchangers, valves and other components are arranged with ample loops to allow for thermal contraction.

Cold box 5 and turbo pod 4 house the primary load circuit elements internal to the refrigerator. Within this volume the primary load circuit traverses heat exchangers 11, 12 and 13 mounted within the liquid pots, the calorimeter when its use is required and the circulation compressor (C3) as well as mass flow meters at the exit to and return from the external load.

The primary load circuit is designed for 20 ATM pressure. The circuit operates at 5 atm during steady state conditions. During cooldown this circuit supplies gas to the external load at 15 atm. Should a magnet quench or other process disturbance occur, the circuit may go to 20 atm before relief venting takes place.

The relief valve for the primary load circuit within cold box 5/TP4 is not sized to vent gas from an external load. The original accelerator design contained about 2×10^6 standard cubic feet of helium when at operating conditions. Overpressure relief for the external load would, of necessity, be positioned along the run of the load circuit and be sized for the rate expected.

It is intended that the refrigerator portion of the load circuit is to be isolated from external sources of overpressure by the closing of isolation valves which are provided. The makeup gas route from the main refrigerator will also be isolated. The shutdown of turbine compressor C3 or the establishment of an internal bypass via the primary calorimeter is under consideration.

Isolation of the external load from the refrigerater also occurs upon rupture of the load circuit within CB 5/TP4 vacuum volume or within the liquid pots. Neither the vacuum vessel reliefs or the liquid pot reliefs are expected to be required to vent much, if any, of the external gas mass in this situation.

The liquid pots are mounted on a frame in the same manner as are the heat exchangers in CB 1 to 4.

Each of the liquid pots is equipped with a 6" relief line closed by a burster disc designed to relieve with an 80 psi differential pressure across the disc. These relief lines vent to the atmosphere outside of the building immediately after penetrating CB 5 vacuum vessel. The design pressure of the pots, however, has been established at 20 ATM. This is done to protect the pots against overpressure from rupture of any of the primary load circuit components (piping or heat exchangers) within the pots.

The turbo pod 4 assembly of CB5/TP4 has mounted on it turbine expander 5, turbine compressor C1/C2 and the already discussed turbine circulating compressor C3.

The low temperature components are within the vacuum envelope.

Heat exchanger HX 15 which cools liquid inbound to the intermediate pot using intermediate pot vapor outbound to the turbocompressor increases plant efficiency by 5%.

All process heat exchangers are brazed aluminum, two pass, counter flow, plate-fin type manufactured by the Trane Company, LaCrosse, Wisconsin.

The LP return circuit working pressure is 6.7 ATM and the HP inbound circuit working pressure is 20 ATM.

The primary load circuit passages in the heat exchangers in the low and intermediate pots as well as the make up passage in the high pot have a working pressure of 20 atm.

All heat exchangers have been designed and fabricated in accordance with the ASME Code for Unfired Pressure Vessels Section VIII.

2.3.2.6 Cryogenic Adsorbers

Dual adsorbers, each in a separate vacuum vessel, are employed to remove trace impurities of nitrogen argon, water vapor and carbon dioxide from the high pressure helium stream.

The adsorbent material is activated coconut shell carbon. Each adsorber bed, 48" diameter and 48" bed length, is designed for a 24 hour onstream cycle. The bed is sized for a design flow rate of 3343 g/s at 69 K and 16 atm with a design impurity of 50 ppm air by volume. Design output purity is less 1 ppm each of nitrogen and oxygen.

The beds are equipped with reinforced glass wool filters at the inlet and discharge and a 10 micron filter downstream of the assembly.

Automatic isolation of the bed in use is provided should a process upset cause the helium stream temperature to rise above the design limit. Flow around the bed is provided by the opening of a bypass valve as the isolation valves close. Provision exists for recooling the bed before it is put back on stream.

2.3.2.7 Turbomachinery

A. Turboexpanders - All turbine expanders are of Rotoflow Corporation manufacture using oil-brake dynamometers to absorb the extracted power. Rotational speeds of the units and other information is given in Table 2-1. The speed is adjustable to give a +10% to -40% range in power extraction.

The turboexpanders extract approximately 350,000 watts of energy from the process under steady flow conditions and almost twice that

CRYOGENIC TURBOMACHINERY

EXPANDER NUMBER	TEMP. IN (°K)	WORK (kw)	IMPELLER DIA. (cm)	SPEED (1000 rpm)
1	185.0	109	11.4	48-50
2	69.5	162	11.4	48-50
3	25.0	42	6.6	48-50
4	12.4	37	7.6	39-44
5	6.3	10	4.4	40
COMPRESSOR NUMBER				
1A	2.5	2.0	10.9	18-20
1B	3.6	2.0	11.7	18-20
2A	4.6	12.4	15.2	18-20
2B	7.1	12.4	17.5	18-20
3	3.47	6.2	10.4	10-11.5

Table 2-1

when both the A&B trains (primary and redundant pair) are operated simultaneously.

These units are of the so called stiff shaft design to insure that the first shaft critical speed occurs well above both the turbine operating and trip speeds.

Shaft support is by means of high-rigidity, rugged-duty combination journal and thrust bearings designed for high speed operation and to withstand excessive loads which can occur with misoperation or with icing of the rotor. The bearing design permits very close tolerances and provides bearings which maintain shaft alignment and protect seals more effectively than the tilting pod type.

The turboexpanders are mounted in turbine pods, i.e. vacuum chambers, and arranged in a way to provide two separate groups of expanders, one (A) redundant to the other (B). Components of one train can be worked on, including components within the insulating vacuum envelope, without disturbing the operations of the companion train.

A rapid-acting trunion type valve closes the inlet to each group of expanders or expander in a train. This valve is closed in approximately 0.4 seconds after initiation of closure and protects against turbine overspeed, excessive vibration, loss of bearing lube oil pressure or loss of bearing oil seal gas. The aforementioned parameters have one level of audible and visual alarm prior to shutdown action.

The seal gas mentioned above is part of the sealing system which is designed 1) to prevent oil migration into the process gas, 2) minimize the flow of warm helium (seal gas) into the process, 3) prevent outleakeage of cold process gas, and 4) minimize the flow of helium into the oil loop.

The seals are of tapered, close fitting labyrinth design with a small flow of ambient temperature helium seal gas delivered to approximately the center of the length of the labyrinth O.D. This seal gas flow divides with a small fraction flowing towards the process side and the remainder flowing towards the oil bearing side and preventing migration of the oil towards the process.

The seal gas pressure is controlled to be 2 to 3 psi above the process pressure.

Variable area inlet nozzle vanes are mounted on the inlet of all turboexpanders. This unit permits flow rate variations of plus 10 and minus 40 percent of steady state design flow rates. These nozzles are used to control flow rate rather than using an upstream throttling valve or bypass. This is the most efficient method of controlling flow as it maximizes energy extraction from the stream by the turbine wheel. The variable area is immediately adjacent to the wheel inlet and velocity head values are preserved.

Where two expander sets are in series; the nozzles for the downstream expander are controlled to match the speed of this turbine with the upstream unit. This insures equal loading and optimum efficiency for both machines.

B. Turbocompressors - The C1/C2 turbine compressor is required to pump helium vapor from the saturation temperature and pressure of the intermediate pot and the low pot to a pressure greater than the main compressor suction pressure plus the refigerator LP return side heat exchanger pressure drop.

The C1/C2 compressor is a single unit with four centrifugal compressor stages on a single shaft. The first two stages, which constitute the low pressure pump, takes suction from the low pot. The second two stages, which is the intermediate pressure pump, receives flow from the first two stages plus the intermediate pot.

Under normal operating conditions the low pressure unit operates with a suction of 0.1 ATM corresponding to the low pot temperature of 2.49 K. The intermediate pressure pump operates with a suction pressure of 0.35 ATM (3.27 K) and will compress the helium vapor to about 1.4 ATM.

The compressor wheel array has a design rpm of about 18,000 and this can be varied up to 21,000 and down to near zero.

A variable speed, 75 HP, DC motor with a design rpm of about 2,500 is coupled to a 7.76 to 1 gear box to drive the compressor. The critical speeds are estimated to be about 35,000 rpm, well above the operating range.

With low heat loads in the pots, the vapor flow from the pots will be reduced. Constant pressure will be maintained by a combination of speed decrease via automatic control and flow bypass back to compressor suction. This method will ensure a maximum surge margin.

The C3 turbine circulating compressor is a single-stage centrifugal unit with a 4.1 inch dia rotor wheel operating at 10,000 rpm. The mechanical arrangement of rotor, shaft, housing, drive, etc. is similar to that of the C1/C2 compressor.

The unit is driven by a 20 HP variable speed dc motor coupled to a speed increasing gear train.

The compressor normally operates with a suction pressure of 4.15 atm and a discharge of 5.45 atm at 3.76 K and with a thruput of 4054 g/s. The compressor is designed to withstand and operate at a pressure of 20 atm. The compressor is designed to accommodate flow variations from -40 to +10% of nominal flow rate.

C. Turbomachinery Alarms & Interlocks - Each expander and compressor is equipped with alarms and interlocks to protect the equipment. These alarms and interlocks have been designed into each of the local turbine controls, are analogs, and do not rely on manual or computer interface to protect the equipment. Each alarm is annunciated at each local turbomachinery control panel by audible means and light indicator.

The control computer monitors each alarm condition and resultant action and can be programmed to take final action if the condition remains.

2.3.2.8 Low Temperature Process Piping

The low temperature process piping interconnects piping circuits between cold boxes, turbine pods and adsorber vessels. The process lines are fabricated from type 304 stainless steel. Lines which operate from 80 K and below are vacuum insulated. Process lines operating above 80 K are closed cell foam insulated with a vapor barrier outer sheath.

The vacuum insulated lines have an outer jacket of stainless steel. The entire system of lines were fabricated in specific spool lengths at the Minnesota Valley Engineering Co., New Prague, Minn. Each spool has its own vacuum volume with long heat path end closures. No bellows are used in the process piping or the vacuum casing. They are, however, used at the vacuum barriers at the spool ends.

The assembly of the spools, requires a progressive fitting of the spools between refrigerator components, with the mounting of pipe supports as the assembly progresses. The process line spool connection is a field welded socket joint. Completed sections of process line, from say, valve to valve or to a temporary welded end cap are given a pressure test as required by ANSI B31.3, Code for Pressure Piping. This test is followed by a helium mass spectrometer leak check.

Upon successful completion of these tests, the vacuum enclosure at the spool joints is completed by first applying layers of superinsulation with packets of gettering material to the process pipe. The vacuum casing consisting of split half shells is then welded in place and the volume is then pumped out.

Leak checks of the vacuum volume are then performed.

Each vacuum volume is equipped with a vacuum pump out connection, a pressure sensor and an overpressure blowout plug which vents when the vacuum volume goes to approximately 5 psig. The design of the piping routes provide sufficient 90° and "U" bends to allow for thermal movement over a temperature range of about 340 K (adsorber bed reactivation temperature) to liquid helium temperatures. The vacuum casing is designed to handle a thermal movement caused by an ambient temperature range of -20F to 120F.

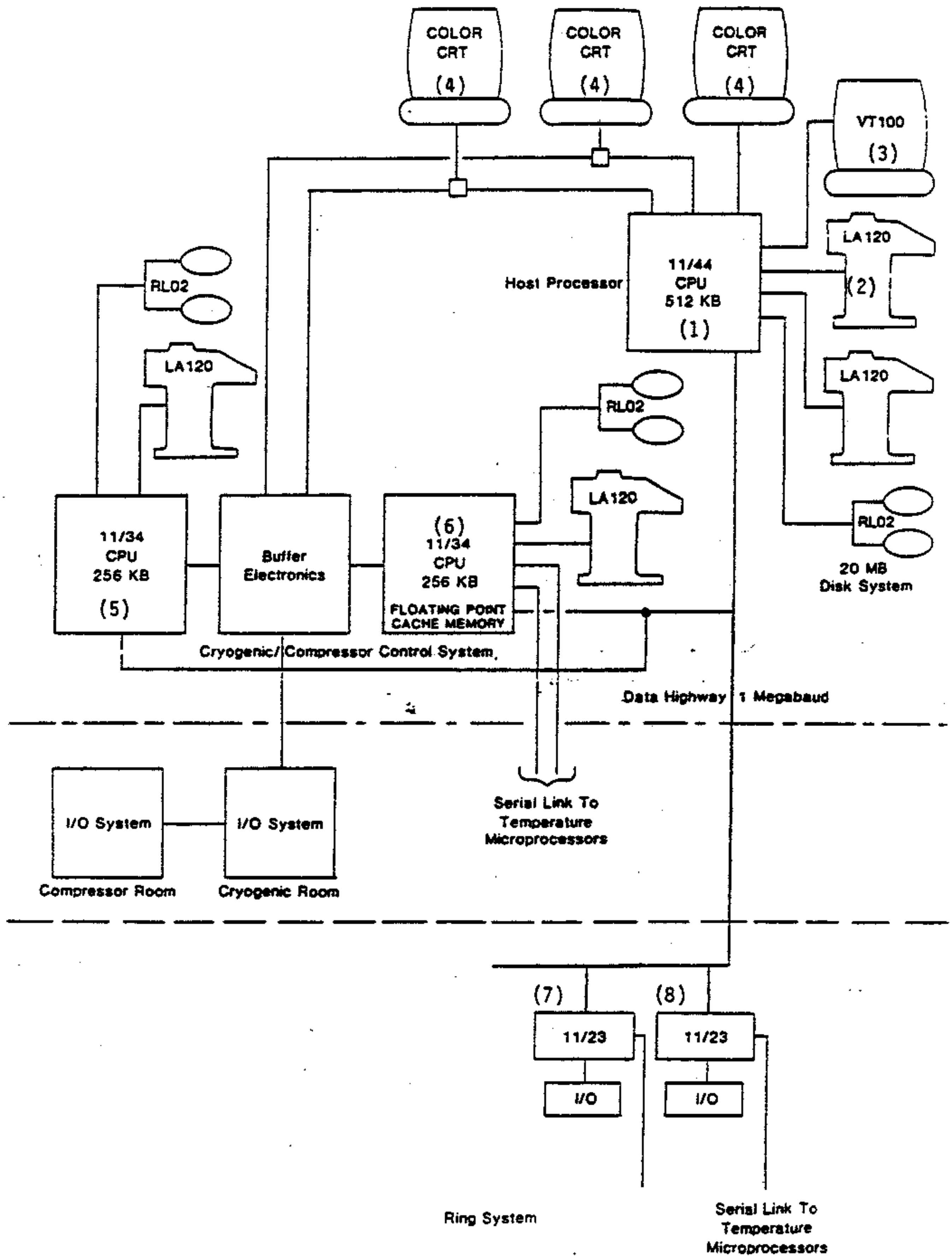
2.3.3 Control System

For control of the cryogenic system, a "standard" industrial process control computer system will be used. The requirements in this regard are so similar to those of the petrochemical industry, that it is possible to choose from a large number of such systems, all well tested and unusually user-friendly. Such a system was purchased in 1981 for control of MAGCOOL, the production magnet testing facility. MAGCOOL has been on line for almost a year now and has proven to be a great success. Benefits realized by using a commercial system for cryogenic control include:

1. It worked the first try.
2. Reduced operating personnel.
3. Less costly than an inhouse developed system.
4. Minimizes operator error.
5. System documentation the responsibility of the supplier, not the user.

Based on our experience a similar approach was taken for control of the CBA cryogenic system. Low bidder proved to be Anaconda Advanced Technology (ANATEC), supplier of MAGCOOL controls. Architecture of the commercial system (Fig. 2-13) is very close to a proposed design outlined in the original BNL specification. At the top of the system is a PDP 11/44 host computer (1) to be located in the local cryogenic operator area. Peripherals include an alarm and logging typewriter (2), program development CRT (3) and three color graphics operator work stations (4). The host provides drive capability for the operator stations and performs communications, polling, data storage and retrival duties between distributed processors via a 1 megabaud data highway.

Compressor room and refrigerator hardware will interface to a distributed PDP 11/34 computer (5&6) with a fully redundant hot backup system in standby. Automatic switchover to the backup computer will occur within one second of active processor failure. Two distributed remote satellite PDP 11/23 systems (7&8) were purchased for cryogenic control duties at sextant positions 4 o'clock and 6 o'clock of the ring. Each consists of redundant design with automatic failover capability. Initially these distributed microprocessors are



Cryogenic Control System Architecture

Figure 2-13

downloaded from the host via the data highway. Loading includes the installation of an operating system, control logic and communications programs so the distributed processors act as standalone process modules with communications to/from the host.

The entire control system is designed for reliability and is extremely tolerant of electronic failure. Normally the operators communicate with the process through the host at the top of the system. If the host fails, the operators can switch two of their work stations to the PDP 11/34 and continue to monitor and control both compressor and refrigerator systems. During the host failure period communciations to the distributed 11/23 microprocessors is lost but they continue to perform their assigned tasks acting as standalone independent systems. All memory has battery backup for power failure protection and the processors have automatic restart upon resumption of normal LILCO service. Standard subroutines permit computer startup with predefined valve patterns and the staggering of compressor start to keep the substation from being overloaded by motor inrush surge currents. Software interlocks and alarms will be used extensively throughout the logic to protect against malfunction. Limits will be placed on certain critical process variables and the operator locked out of process areas where there is no need to provide interactive capability. A final level of safety exists directly at the hardware in the form of mechanical relief valves and/or hard wired interlocks which protect the system from operating conditions that could possibly cause mechanical damage.

The ANATEC system was received July, 1983. Final in-house acceptance tests were completed in November, 1983. Applications programming began in January, 1984.

3.0 OPERATING PROCEDURES, TRAINING AND ADMINISTRATION

3.1 Responsibilities for Safety, Operation and Maintenance

Safety is a line responsibility extending throughout the line organizations to all BNL employees. The Head of the Accelerator Development Branch (ADB) of High Energy Facilities (HEF) has line responsibility to implement the BNL safety policy at this facility. The Cryogenic Division Head is responsible to the ADB Head to assure that these policies are adhered to by the Cryogenic Division personnel who will operate and maintain the equipment in this facility.

A HEF Safety Committee advises the ADB Head on matters of safety, but has no line responsibility.

The Associate Director for Safety has requested that this facility be reviewed by one or more BNL standing safety committees so that said committee(s) may comment and make recommendations with regard to the safety of the operation. This report is prepared for presentation to the reviewing committee(s).

3.2 Operator Training

The helium refrigerator is a complex system and requires careful, perceptive operation to develop its full capability. Wherever possible automatic controls have been provided where the process is amenable to such control. There are some processes and interactions between processes which can only be controlled by operator intervention. This is especially true during start-up and shutdown of the system. The system has been designed so that there is protection (relief valves, etc.) against operator error wherever possible.

3.3 Operating Instructions

Written operating instructions will be provided by Koch Process Systems, the supplier of this equipment. The technicians who are to operate the plant will receive classroom instruction to familiarize them with these instructions. The operators have general expertise in the cryogenic field and specific experience with the classes of equipment, although smaller in size, used in the plant.

3.4 Operating Limits, Emergency Procedures and Test Plan

An overall Test Plan will be developed before Acceptance Testing of the plant begins. Incorporated into the Test Plan will be Emergency Procedures covering operator response for power failure, rain/flood, fire and oxygen deficiency. Operating limits (which are the system parameter boundaries within which the operators may operate at their option and outside of which they must follow a prescribed course of action) will also be incorporated into the Test Plan. This test plan will be reviewed in committee and all proposed actions carefully weighed. The Cryogenic Division Head is chairman of this committee and has line responsibility for safety as well as other aspects of the testing.

4.0 HAZARDS AND CONTROL

4.1 Hazards

4.1.1 Cryogenic Fluids

Cryogenic liquids present significant hazards because of their intense cold and substantial gas production when warmed. The extreme cold not only can cause tissue damage to personnel, but also can bring about changes in the properties of metals and other materials. Asphyxiation and overpressure hazards are created by the potential for production of large quantitites of gas. These problems require that careful attention be given to the storage, transfer, and use of cryogenic liquids in order to assure the safety of personnel working with them.

4.1.2 Asphyxiation

Mechanisms do exist which could result in the release of helium or, possibly, nitrogen into enclosed areas. The quantity and rate of gas that may be released is dependent on a number of variables. The principal consequence of these accidents is the creation of an oxygen-deficient atmosphere. In this analysis, any atmosphere with oxygen concentrations of 19.5% or less is defined [by OSHA 1910.94(d)(9)(vi)] as oxygen-deficient. The potential biological effects of human exposure to oxygen deficient atmospheres (see Table 4-1) are a strong function of the oxygen concentrations and the length of exposure.

For example, exposure to concentrations of less than 6% oxygen can produce death in a short time, while exposures to 19% oxygen concentrations for a long time are expected to produce only imperceptible physiological reactions. Sudden changes in oxygen concentration (similar to the consequence of a major accident in the tunnel) have been studied in conjunction with flying at high altitudes. These studies indicate that even for drops in concentration

TABLE 4-1

Effects of Exposure to Reduced Oxygen

PO_2 (mmHg)	$\%O_2$ (at 760 mmHg)	Reduced Night Vision	Increased Ventilation Rate	Reduced Judgement Memory, Motor Movements	Time to Loss of Consciousness (minutes)	Time to Coma (minutes)
159-73	20.9					
135	17.8	Threshold				
131	17.3	23%				
117	15.4		Threshold			
114	15.0			Threshold		
110	14.5	59%				
105	13.9			20%		
92					Threshold	
89	11.7	required increase in illumination to see equal detail		50%		
86-73	11.4-9.6		1.65 x normal	80%		
73	9.6			-	20	-
64	8.4		no further increase		5	
60	7.9					10
56	7.4					5
52	6.9				1	
49	6.5					2
35	4.6					1
32	4.2				1/2	

Guyton AC (1971): Textbook of Medical Physiology, Fourth Edition.
W.B. Saunder Co.: Phildelphia, pp. 518-521.

to as low as 10% that diminished physiological capacity would not result in an inability to respond for periods of up to 10 minutes.

4.1.3 Pressure Vessel or Piping Failure

A major failure of certain pressure vessels or interconnecting piping could result in the release of significant quantities of helium or nitrogen into areas occupied by operating personnel. The maximum quantity available for release in each location is listed in Table 4-2.

Vessels or piping may fail while subjected to normal (i.e., within the designed range) operating conditions from causes related to improper design, material selection or assembly. Vessels or piping may also fail if they are subjected to abnormal operating conditions due to instrument or control failure and/or operator error.

4.1.4 Noise

The effects of noise on people take many forms; it can be physiological or psychological in nature. These effects include permanent hearing loss, temporary hearing loss, interference with speech communication and various stress reactions. The effects of noise increase with both the intensity and duration of the noise exposure. Continued exposure to high-intensity noise such as generators, motors, or industrial processes can result in a loss of hearing.

It is expected that high noise levels will be encountered in the Cryogenic Wing and, especially, the Compressor Room.

4.1.5 Fire

No flammable cryogenic fluids are used in this system.

Table 4-2

24.8 kW REFRIGERATOR

APPROXIMATE QUANTITY OF GAS BY LOCATION

Thousands of Standard Cubic Feet

LOCATION	HELIUM				NITROGEN	
	Capacity		Normal Operation		Capacity	Normal Operation
Gas Storage (out-of-doors)						
Buffer Tanks		160		9	0	0
Bubble Chamber Tanks		2500		50	0	0
Liquid Nitrogen (out-of-doors)		0		0	1200	800
Compressor Building		48		48	3	3
Cryogenic Building						
Cold Box #1	5		5			
#2	5		1			
#3	12		12			
#4	80		80			
#5	480		480			
Other	26		20			
Total Cryogenic Building		608		598	—	—
Cryogenic System Total		3316		705	1203	803

Oil will be used as a lubricant and as a hydraulic fluid (in the turbine brake circuit). Table 4-3 shows the quantity and location expected. All oil is in closed systems.

No special fire hazards are anticipated.

4.1.6 Electrical

No special electrical hazards exist in this system.

4.1.7 Mechanical

No special mechanical hazards exist in this system.

4.1.8 Radiation

No radiation hazard exists in this location.

4.1.9 Magnetic Fields

No magnets are used in this system. The only magnetic fields are those generated in standard equipment, e.g., electric motors.

4.1.10 Explosive and/or Flammable Gases or Liquids

See Section 4.1.5.

4.1.11 Toxic Materials

No toxic materials are used or handled in this system.

4.1.12 Air Pollution

There are no air pollutants released by this system during operation or maintenance periods.

4.2 Controls and Quality Assurance

4.2.1 Policy

The buildings which house the refrigerator have been built in accordance with the applicable Federal and N.Y. State Codes. Electrical installation, fire protection, exits and all other features of the buildings are

Table 4-3

24.8 kW REFRIGERATOR

APPROXIMATE QUANTITY OF OIL BY LOCATION

LOCATION	QUANTITY Gallons	TYPE
Compressor Building	4400	UCON 170 Flash Point: 450 °F
Cryogenic Building	1200	Light Spindle Oil Flash Point: 380 °F

also in accordance with the applicable codes. The help and guidance of the S&EP Division has been utilized for interpretation of these codes.

4.2.2 Quality Assurance

The refrigerator system is supplied by the Koch Process Systems, Inc. The contract with them specifies a quality assurance program that applies to the materials and fabrication techniques used in the construction of our equipment. Compliance was checked by the CBA Quality Assurance Officer and by the cognizant Cryogenic Division Engineer. A quality control inspector based near Koch was engaged to regularly visit the Koch plant and report to BNL his findings. The documentation from this quality assurance program is part of the delivery to be received from Koch under their contract and will include reports of all testing.

4.2.3 Safeguards

4.2.3.1 Cryogenic Fluids

Cryogenic fluids will be handled in accordance with BNL Safety Manual, Section 5, Cryogenic Safety.

4.2.3.2 Asphyxiation

Oxygen deficiency monitors will be installed in each of the buildings. Figures 4-1 and 4-2 show the location of the sensors. These will sound an alarm in the refrigerator control room if oxygen concentration falls below 19.5%. Because of the expected high noise levels, strobe lights as well as audible alarms will be used. Tests[1] have shown that helium gas released into air will rise and stratify. Thus, because the buildings are rela-

---

[1] Oxygen Deficiency Hazard Induced by Helium Release in Accelerator Tunnel, D.P. Brown and J.H. Sondericker, 1983 Particle Accelerator Conference, March 23, 1983.

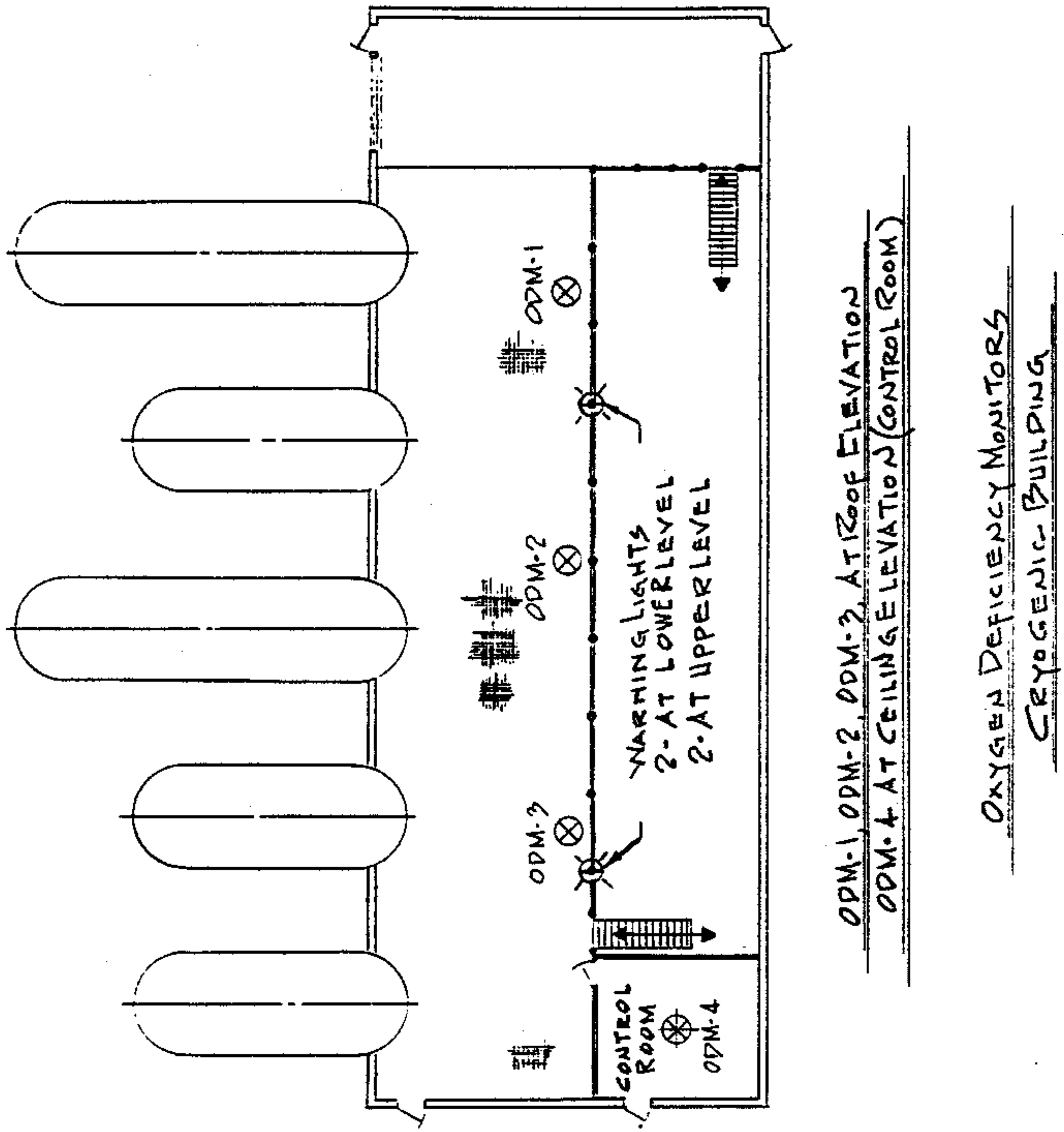


Figure 4-1
Oxygen Deficiency Monitors, Cryogenic Building

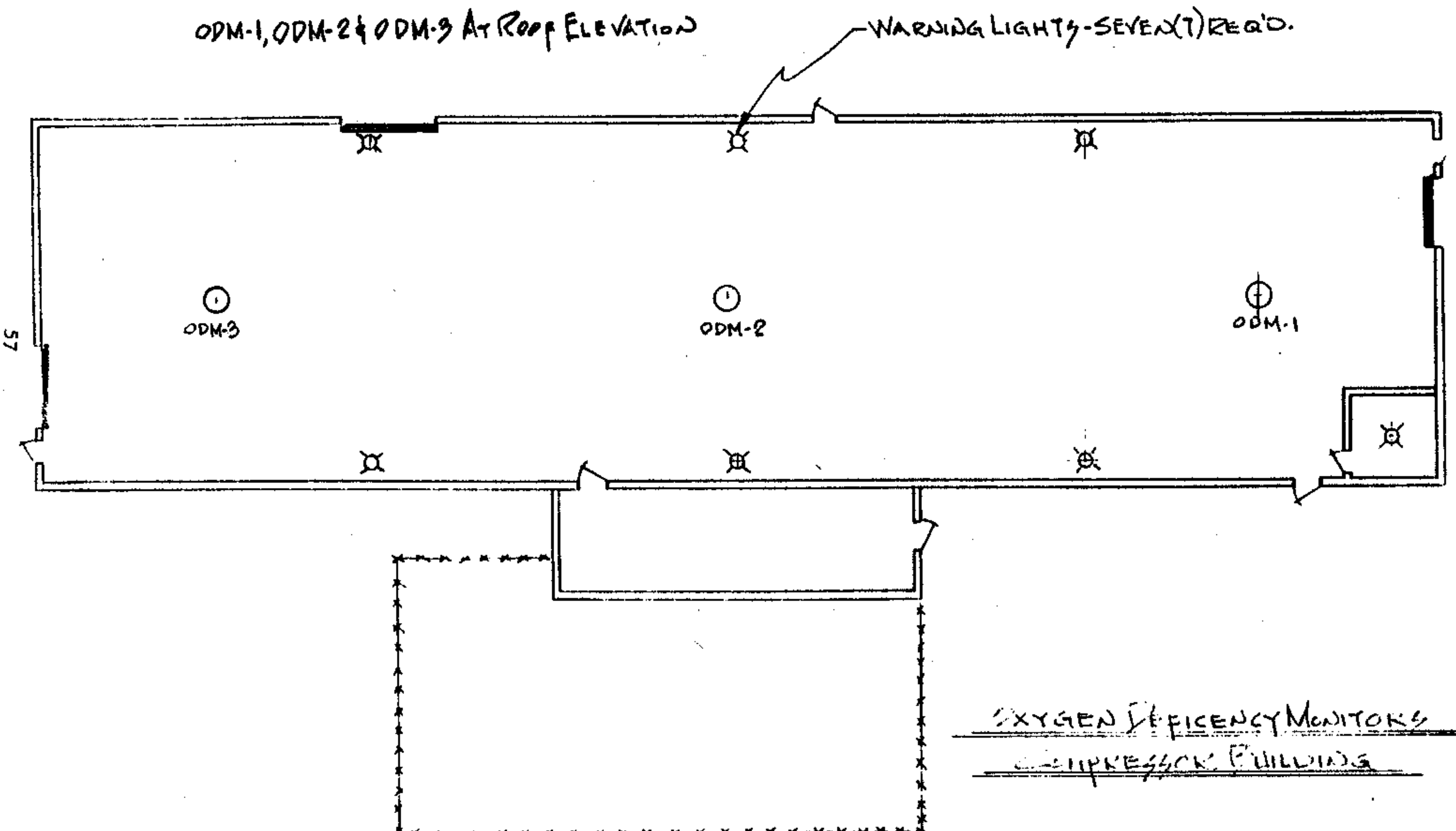


Figure 4-2
Oxygen Deficiency Monitors, Compressor Building

tively high compared to the elevation of the occupants, there is a large margin of safety.

Both of these buildings are equipped with ventilation systems which can draw fresh air into the building in case there is a low oxygen level. The location and capacities of these ventilation systems are shown in Figures 4-3 and 4-4.

The Operating Instruction section for Emergency Procedures will require that the operators operate the exhaust fans whenever an oxygen deficient atmosphere is indicated by the oxygen deficiency monitors. The fans may be run at the operator's option when the oxygen concentration is more than 19.5%. The compressor room fans will be run for a large percentage of the time that the compressors are operating. This will be necessary in order to exhaust the air which is heated by virtue of the operation of the electric motors driving the compressors. In extremely cold weather it might be possible to run the compressors with the roof fans off and still maintain a comfortable temperature in the building.

The possibility of asphyxiation cannot be discounted out-of-hand because the quantity of helium, if it were at ambient conditions, contained by the piping and vessels is, in some cases, greater than the colume of the building. The extreme example of this occurs in the Cryogenic Building. Cold Box 5 contains cold helium which at ambient conditions would displace 480,000 cubic feet. The Cryogenic Building has a volume of 240,000 cubic feet. If all this helium was released instantaneously into the Cryogenic Building and formed a homogeneous mixture with the air, the oxygen content would drop to about 7% which (see Table 4-1) constitutes a severe hazard. There is even the possibility that the helium could displace the air entirely.

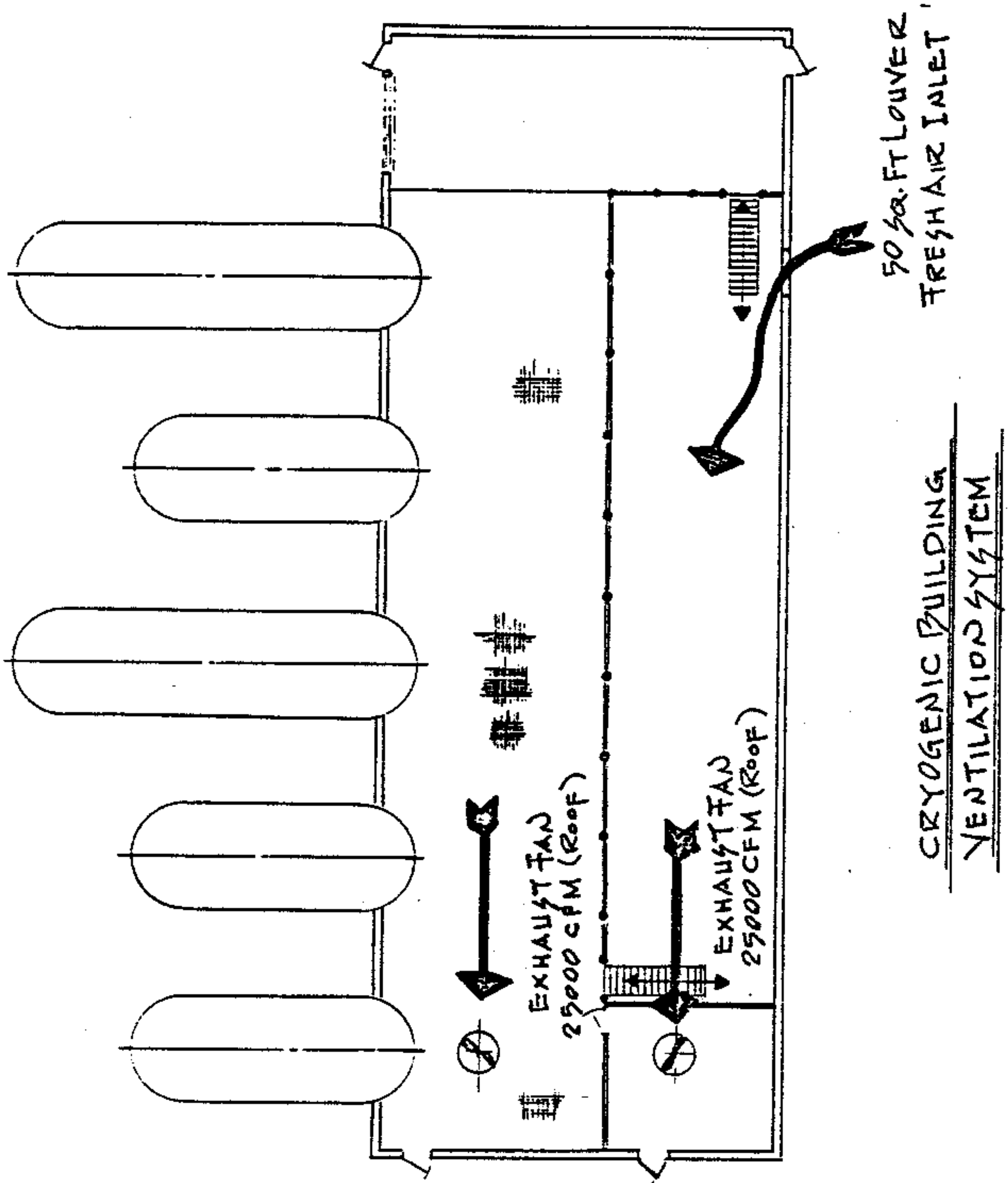


Figure 4-3
Cryogenic Building
Ventilation System

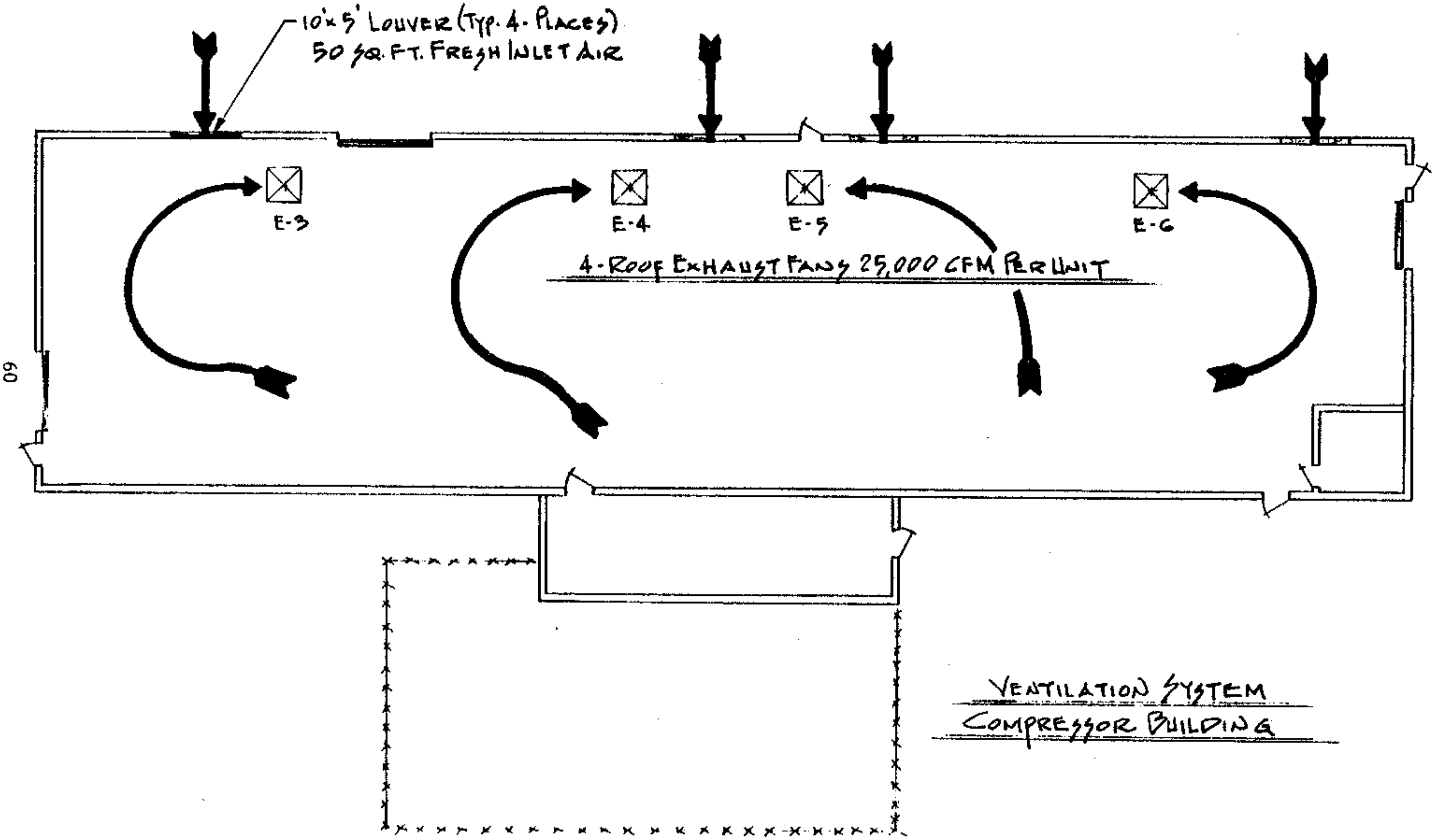


Figure 4-4
Compressor Building

While it is impossible to predict exactly what will happen in the case of a major equipment failure, it may be useful to examine an accident beyond the usual single failure mode analysis to get a feeling for the consequences of a double failure.

A double failure is necessary to produce this condition because all the helium volumes of consequence are at very low temperature and, therefore, must be vacuum-insulated to prevent undue heat leak. In order to produce a significant release, both the process piping or vessel must fail and the vacuum tank must fail in such a manner as to deliver the helium into the building. The possibility of occurrence for either of these events is extremely low.

Most of the helium in Cold Box 5 is in liquid form and resides in the three vessels (see para. 2.3.2.4) which share the insulating vacuum space of the cold box. Two of these vessels are normally at a pressure below atmospheric and the third is at 1.4 atmosphere absolute (6.2 psig). These vessels are physically in the part of the cold box which is outside of the building.

Suppose a very large truck were to strike Cold Box 5 and impart enough energy to shift the cold box off its mountings. Further suppose that the three liquid-containing vessels inside were to move in such a way that some of their connecting piping is severed. Also suppose that when the vacuum tank shifts it breaks the short piece of pipe between the vacuum tank and the vacuum system isolation valve. This pipe is located inside the building.

When the liquid helium spills into the vacuum tank and evaporates, the pressure will rise. The helium can find its way out through the break assumed in the vacuum pump pipe and/or through the two 10-inch relief valves on the vacuum tank. These valves will relieve when the pressure is above 0.1 psi. The rate at which helium enters the room is a function of the pressure in the vacuum tank and the size of the break. The pressure in the tank is a very complicated function of heat transfer inside and outside the vacuum tank, liquid helium level at initial conditions, leakage rate, etc. For this exercise, assume that the conditions in the tank are such that the pressure in the vacuum tank rises to 2 psig.

The two 10-inch relief valves have a combined flow area of about 1,000 sq. cm. If the broken vacuum pipe has the flow area of a 10-inch hole (√500 sq. cm.), then one-third of the helium will go into the room.

The vacuum tank has multi-layer insulation. Even though the vacuum has failed this will considerably retard heat transfer from the warm vacuum tank to the helium. A heat transfer rate of 0.002 to 0.003 W-cm^{-2}-K^{-1} is frequently used for cryogenic temperature vent lines in air. Assume 0.003 W-cm^{-2}-K^{-1} for the rate at the vacuum tank interface and at the cryogenic vessel surface. On this basis, the calculated time to evaporate the 19,200 liters of liquid in Cold Box 5 is then six minutes. This will generate the equivalent of 480,000 SCF of helium. One-third finds its way into the building at the average rate of √27,000 SCFM.

This helium gas would warm as it contacted the environment outside of the vacuum tank. When the ODM alarm sounded the operator would turn on the roof fans. These fans would remove 50,000 CFM of helium-air mixture. This mixture would probably be very rich in helium at the roof level in the vicinity of Cold Box 5 so much of the helium would be removed by the fan at that end of the building.

The personnel hazard associated with such an accident is very low except in the immediate vicinity of the leak. Any personnel close to this point could suffer injury from freezing and/or death from suffocation. The danger area would probably be quite small in area and enshrouded in fog due to condensation caused by the low temperature helium. Therefore, it is not likely that anyone will unknowingly enter the area after the event begins.

The building make-up air intake is located along the south wall between the 75-foot and 83-foot elevation. At this location it is least likely to allow a recirculation of vented air/helium mixture.

The refrigerator control room is air conditioned and its air supply is from out-of-doors. The control room is the area of highest occupant density, therefore, the exposure to the asphyxiation hazard is minimized.

4.2.3.3 Pressure Vessel or Piping Failure

This equipment has been designed and fabricated according to the ASME Pressure Vessel Code, Section VIII and ANSI B31.3A, Refinery Piping Code. Testing will be performed in accordance with th these codes.

Where vessels or piping are to operate at cryogenic temperatures the material used is chosen to retain ductility at cryogenic temperatures. Cracks or other flaws which might somehow be initiated do not propagate to catastrophic size because of the material ductility and because even a small leak is soon evident when the insulating vacuum fails and causes a large increase in the heat load resulting in an aborted test or run. The heat load would increase by a factor of about two when the vacuum spoils from 1×10^{-4} to 3×10^{-3} Torr.

4.2.3.4 Noise

The hazard due to the high noise level in these buildings will be evaluated and safeguards instituted in accordance with BNL Safety Manual, Section 2.4, Noise. The noise level in the Compressor Building will probably exceed 95 dBA. Personnel entering this area will be required to wear ear plugs or ear muffs. When the system is operational, the noise level will be measured and appropriate measures taken.

4.2.3.5 Fire

The oil located in these buildings has a relatively high flashpoint (Table 4-3) and is contained in closed, metal sumps. The largest sump has a capacity of about 300 gallons. The gas over the oil in the sump is helium.

The fire alarm and protection system has been described in Section 2.2.6. This system coupled with the absence of any highly flammable materials in these buildings minimizes the fire hazard.

4.2.3.6 Electrical

Electric systems involve 13.8 kV in the substation and 4160 VAC in the compressor motor power circuits. In addition, the normal power distribution system has circuits of 110, 220 and 460 VAC.

The power distribution has been installed in accordance with the National Electric Code and other codes which specify the equipment to be used and how it must be installed. All exposed power bus and other conductors are covered to prevent accidental contact.

The safe operation of the electrical system depends about equally on design, training and administrative procedures. It is our intent to prepare and exercise these procedures very carefully.

4.2.3.7 Life Safety (Egress)

It is generally agreed that a prompt and safe egress from a building is usually the single most important element in the overall life safety design. The principles of the NFPA Life Safety Code which are promulgated in BNL Safety Manual, Section 4.1.2, "Means-of-Egress" are requirements for BNL buildings.

Under the NFPA "Life Safety Code", a building is classified according to its intended use, contents and occupancy level. On the basis of this classification the building is required to have certain characteristics especially with regard to number of exits and travel distances to exits.

The two buildings in which the refrigerator is housed can reasonably be classified as ordinary or general industrial usage. Ordinary hazard contents are classified as those which are liable to burn with moderate rapidity or to give off a considerable volume of smoke, but from which neither poisonous fumes nor explosions are to be feared in case of fire.

Under this classification, with a sprinkler building, the travel limit to an exit is 150 feet. In the Cryogenic Building (see Figure 4-5) the travel distance is 100 feet and it is 60 feet in the Compressor Building (see Figure 4-6). The buildings, therefore, meet this requirement. They also are in compliance with the other aspects of this code.

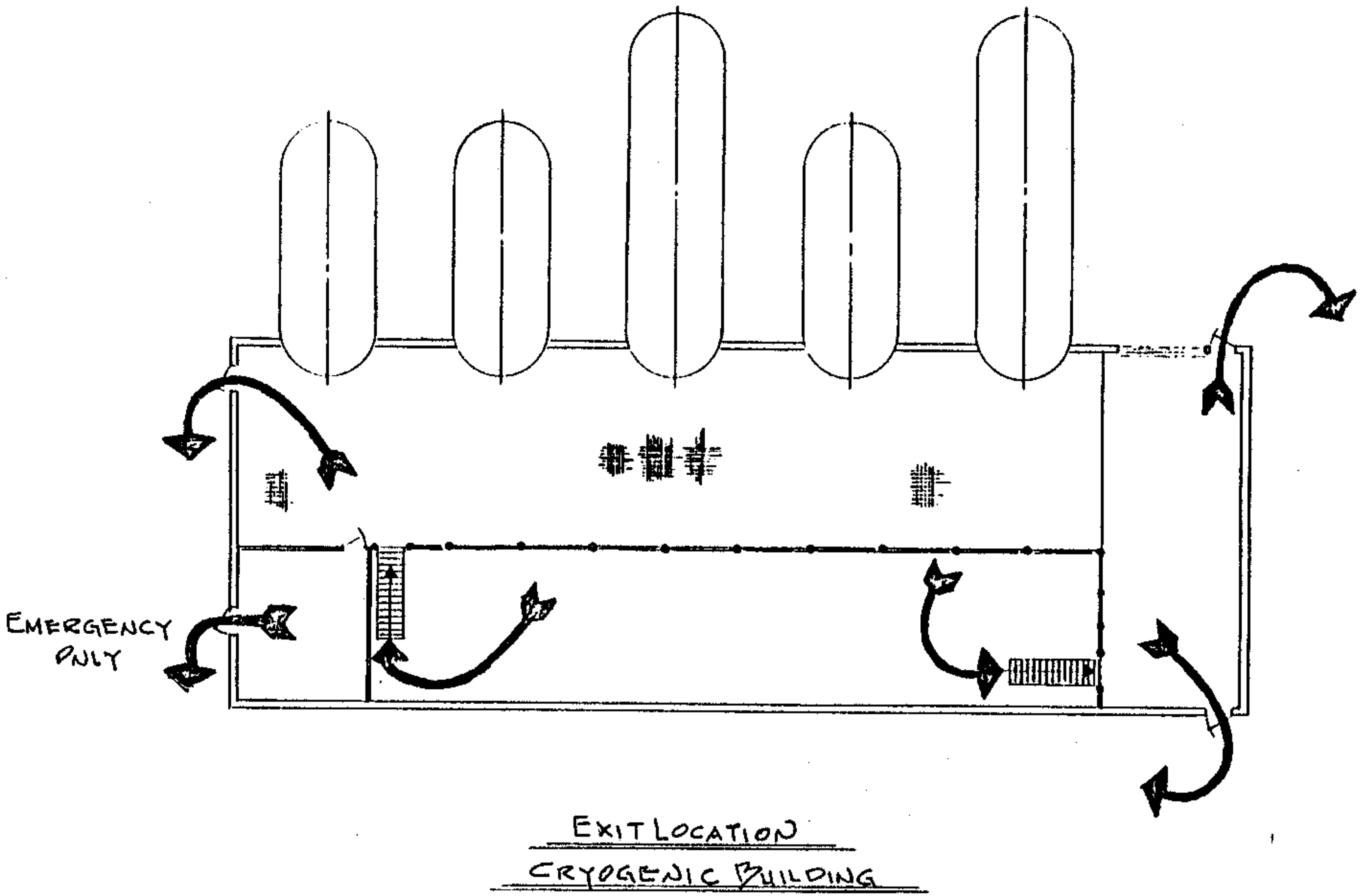


Figure 4-5
Exits, Cryogenic Building

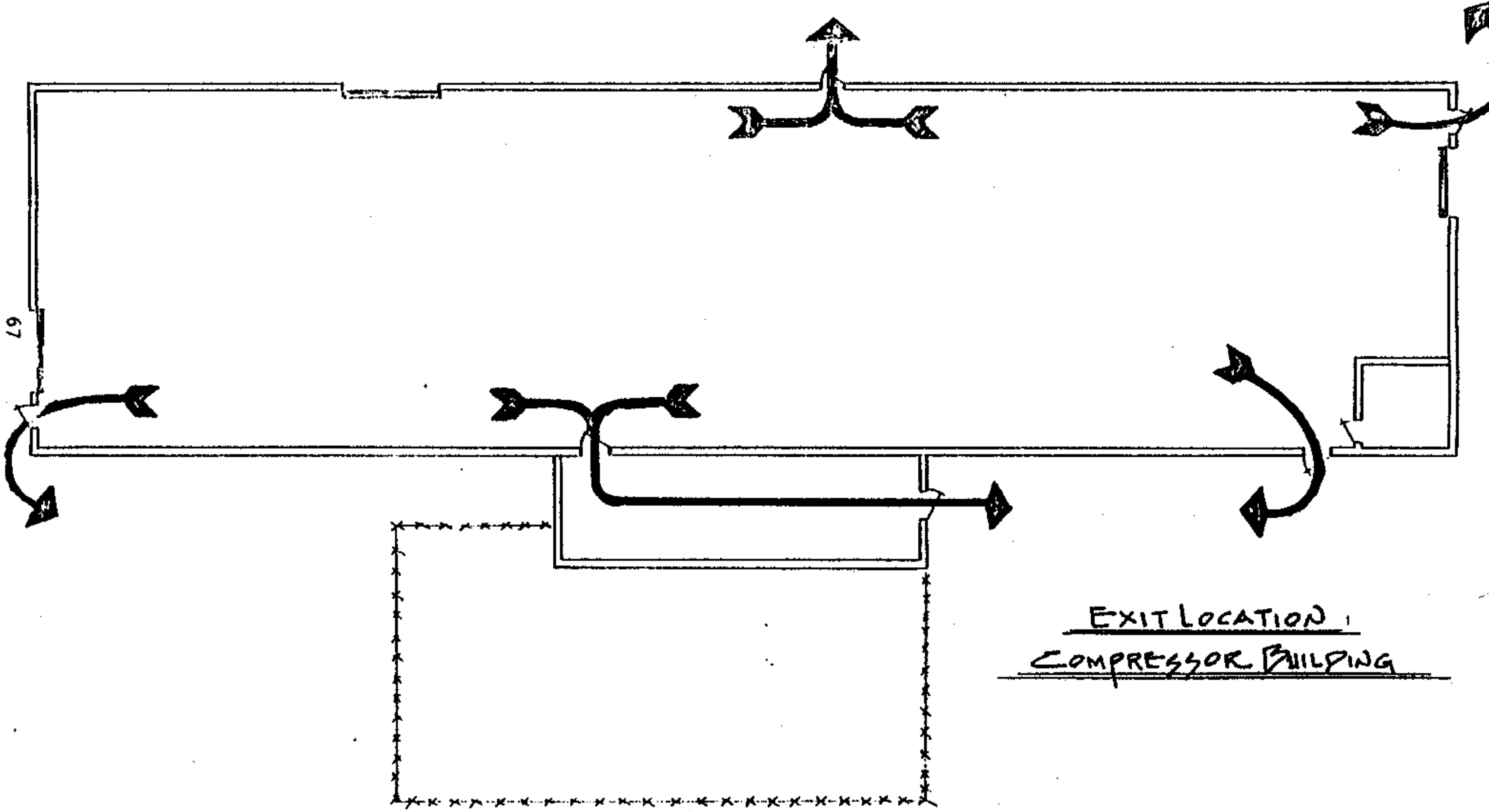


Figure 4-6

5.0 ACCIDENT ASSESSMENT

For the most part, the nature and magnitude of the hazards associated with the Helium Refrigerator are not substantially different from those encountered frequently in industrial facilities. The controls that have been described in the previous sections are those prescribed in BNL and DOE orders and should assure that the risks of fatality or serious property loss are no higher than those commonly prevailing in similar work locations.

The only exception to the commonplace hazards is the asphyxiation hazard which is discussed in the following paragraph.

5.1 Asphyxiation

In the original discussions of safety regarding the ISABELLE/CBA Cryogenic System it was anticipated that the asphyxiation hazard in the tunnel would require special consideration. This was due to the rather small cross-sectional area of the tunnel, the large quantity of helium contained in the equipment and the travel distance to exits. Those conditions are not found in these buildings which are well-ventilated, contain only a comparatively small amount of liquid helium and have good provisions for egress. Therefore, we do not feel that the asphyxiation hazard is severe enough in these buildings to warrant special concern with regard to life safety.

When the Cryogenic System is expanded to provide cooling for a "load" in the tunnel this analysis will be revised to address the problems peculiar to the tunnel.